AUTONOMOUS CONTROL OF COMPRESSED AIR PLANT

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Summary

An automatic control system for the air compression plant, composed of seven compressors divided into two groups, was depicted in this paper. The system was designed to integrate the control, monitoring and diagnostic functions into one device and provide the system operator with a complete system control tool. The main purpose of the system was to enable the operator to prevent manual control and change his role into a system supervisor. The profits from the installation of the system were clearly visible as the machine failure rate dropped and all the critical process characteristics stabilized shortly after the system was implemented. The compressor plant could work autonomously for long periods of time and the performance of the entire plant has risen.

Keywords: automatic control, process monitoring, centralised production of compressed air, process capability

Sterowanie autonomiczne zespołem sprężarek

Streszczenie

Przedstawiono system automatycznego sterowania stacją wytwarzania sprężonego powietrza, złożonej z siedmiu wysokowydajnych sprężarek podzielonych na dwie sekcje. Funkcje sterowania, monitorowania oraz diagnostyki zintegrowano w jednym urządzeniu, wspomagającego operatora w nadzorowaniu przebiegu procesu technologicznego. Głównym zadaniem opracowanego systemu było zautomatyzowanie działań sterujących realizowanych dotąd przez operatora oraz zamiana jego funkcji w nadzorcę procesu. Wdrożenie systemu automatycznego sterowania skutkowało wyraźnym zwiększeniem niezawodności pracy stacji oraz ustabilizowaniem wartości krytycznych charakterystyk jakości. Proces wytwarzania sprężonego powietrza przebiega z dużą wydajności i w pełni automatycznie.

Słowa kluczowe: sterowanie, monitorowanie procesu, wytwarzanie sprężonego powietrza, zdolność procesu

Introduction

An original control system for a compressed air plant was presented here. The compressed air plant, composed of seven independent machines (compressors), was providing the air to a medium-size manufacturing system by

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means of two air lines: 0.6 MPa and 0.3 MPa. The control system was developed to address the problems of poor control quality of the previously used manual system. The compressed air was used in various operations on the shop floor, such as driving pneumatic actuators, transportation of powdered materials, silo maintenance or cleaning.

The centralised structure of the compressed air production system, the size of the distribution network and the number of the connected devices (air sinks) made the air demand planning a very difficult task. Hence, no static compressor work plan could be used in the plant and the continuous presence of the operator was required in the control room. In the previously used control system, the individual compressors were switched on and off manually by the operator, who depended on his knowledge, experience and on the actual readings from pressure gauges. The knowledge and experience of the operator were important factors for the quality of the process (stability of the air pressure) as the volume of the installed pressure buffers was not very high.

The main reasons for the automation of the control process were: the need for stabilising the pressure fluctuations, the need for reducing the operator presence time in the control room (high noise level), the requirement for better documentation of the work and maintenance history for each compressor and the need for reliable data on production costs. The automation of the compressed air control was also a step towards the integration of the entire production process.

The control system design

The system controls the work of the seven compressors divided into two groups. The first group, consisting of four machines connected in parallel, was supplying air to the 0.6 MPa line, while the second group, containing three machines, was connected to the 0.3 MPa line. The control system was composed of the measurement devices (temperature and pressure gauges and alarm switches mounted directly on the compressors), the PLC controller and the operator's console. Optional consoles could be mounted in the remote control rooms if necessary.

The general scheme of the control system was shown in Fig. 1. The operator could communicate with the system by means of specially designed PC-based workstation with built-in keyboard and the LCD display. Standard components of a PC computer (main board, hard disk drive, LCD panel) were used for the construction of the operator's terminal (communication unit) [1].

After the installation of the system the role of the operator changed. The operator was no longer involved in direct control of the system (for example switching the machines on and off), he became the system supervisor instead. As it was shown on Figure 1, the task of the operator was to adjust the set points and the control parameters. The operator was still able to control the machines manually (arbitrary) but it was only an emergency procedure. All the process variables could be accessed and presented on the terminal screen either in the form of current value display or history chart for a preselected period of time.

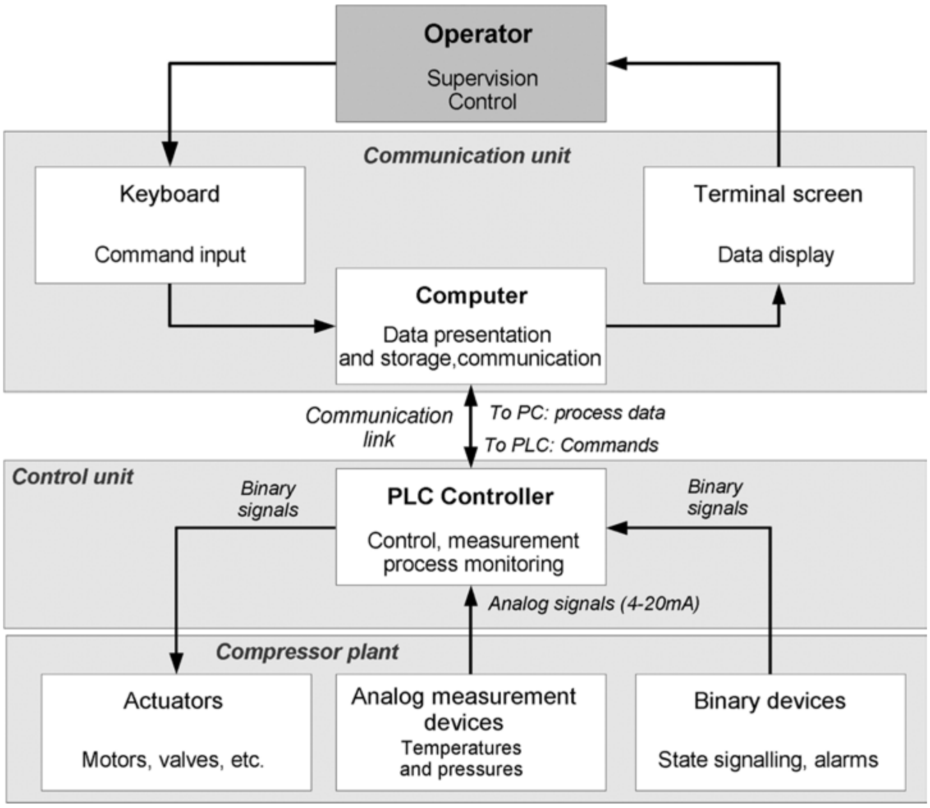

Fig. 1. General scheme of the control system

A Programmable Logic Controller (PLC) was used for the direct control of the compressors. The controller and the communication terminal were connected by a serial link (RS232). All electrical signals from the compressed air plant were connected directly to the PLC. The PLC controller was also acting as a primary process monitoring device [2].

As an option, additional terminals could be connected to the system by a local network to provide remote monitoring and control capabilities.

All the control algorithms and emergency procedures were programmed in the PLC. Therefore the control system could operate even when the communication module (or the communication link) was down.

The communication module was designed to be the operator's interface to the control system allowing to observe the most important control variables and set the control parameters. The interface software had the following capabilities (functionalities):

- presentation of current values of process variables including compressor state, measurement devices readings, water and oil levels, etc. in numerical values or time charts with nominal control and alarm levels,
- alarm notification – as graphics, text (system log) and acoustic signals,
- alarm and event logging (the time of parameter change, etc.),
- process history logging (all process variables and parameters),
- process history display for any period of time,
- parameter value set up (including all the numerical values and binary switches).

The control program in the PLC has the following functions:

- process monitoring – analysis of trends in process variables, counting the machine working time, observation of current temperature (air, coolant and oil) and pressure (oil, coolant) values for each machine, etc.,
- alarm notification – also by means of the independently mounted alarm lamps,
- monitoring of the machines in manual control mode (compressors switched on and off by the operator),
- control of the compressed air production in fully autonomous mode (no presence of human operator required).

The control algorithm

Similar virtual controllers controlled both groups of compressors. The controllers were programmed in the PLC and were connected to the controlled object by a binary control signal *S* and the analogous feedback signal *P* as shown in Fig. 2. *S* was an array of three-state signals as each of the compressors in the group could be put in one of the three states: stop, idle (motor running, air not being pumped), work (normal operation). The feedback was the air pressure measurement taken at the compressor room exit point converted in place to the 4-20 mA analogue signal. The feedback signal had to be filtered as the noise level was very high due to high acoustic pressure and vibrations in the compressor room. A moving median filter was used for the purpose as it allowed decreasing the total delay of the control loop.

A multiple output on-off controller with hysteresis (switching delay) set to match the control limits was programmed for each compressor group. Additional logic was implemented for sequencing the compressors. The sequencing logic was turning on and off compressors according to the pressure fluctuations (caused by the changing air consumption) and the technological restrictions of the individual compressors (maximum continuous work time allowed, maximum temperatures, etc.). The controller could work in two modes: in normal control mode or in predictive control mode. In normal control mode the behaviour of the controller was identical to classical on-off controller. In predictive mode the switching and sequencing of the compressors was made on the basis of actual feedback value and the feedback (pressure) prognosis calculated from the process history. The prediction of the pressure value in the next moment was introduced to compensate the delay in the control loop caused by signal measurement and filtering and by the delay in pressure propagation from the compressor to the measurement point. The algorithm used for the calculation of the pressure prognosis was similar, but not identical, to the signal derivative calculation in a standard digital PID controller. The controller for each compressor group was tuned on-site during the system start-up (implementation) phase.

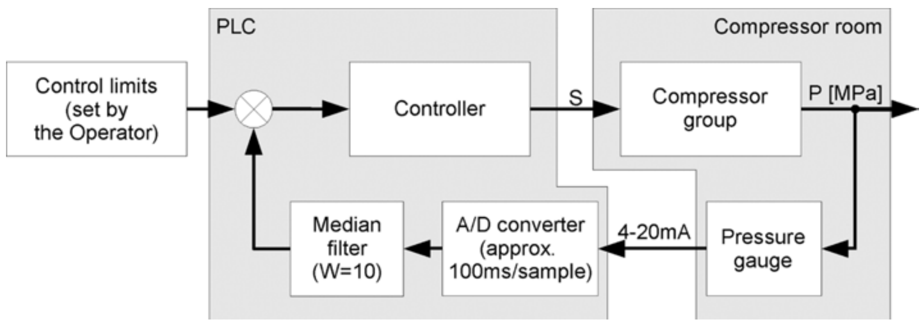

Fig. 2. Scheme of the designed controller

In order to evaluate the efficiency of elaborated control algorithms, the analysis of process capability [3-5] was made. The value of air pressure produced by the compressor plant (0,6 MPa section) was treated as the process quality characteristics. The nominal (target) value of pressure was fixed at T = 0.565 MPa. The specification limits were LSL = 0.525 MPa and USL = 0.605 MPa according to the process requirements.

Two sets of recorded data of air pressure were analysed: for a standard control algorithm (without prediction) and for the process controlled by the optimised algorithm. The data were collected during similar process conditions (requirements of airflow) for the periods of approximately five hours.

The evaluation of process quality using capability ratio (potential or real) assumes that distribution of analysed process variable (quality characteristics) is Gaussian or nearly Gaussian random variable distribution. Otherwise, the appropriate variable transformation must be done [2]. Thus, the estimation of compressed air pressure distribution was made first. Figure 3 shows quantile-quantile probability plots for two sets of air pressure data collected for standard control algorithm (A) and for algorithm with prediction feature (B). It can be seen that there are some deviations from Gaussian distribution for high values of pressure in both cases (too few numbers of recorded points over 0.61 MPa).

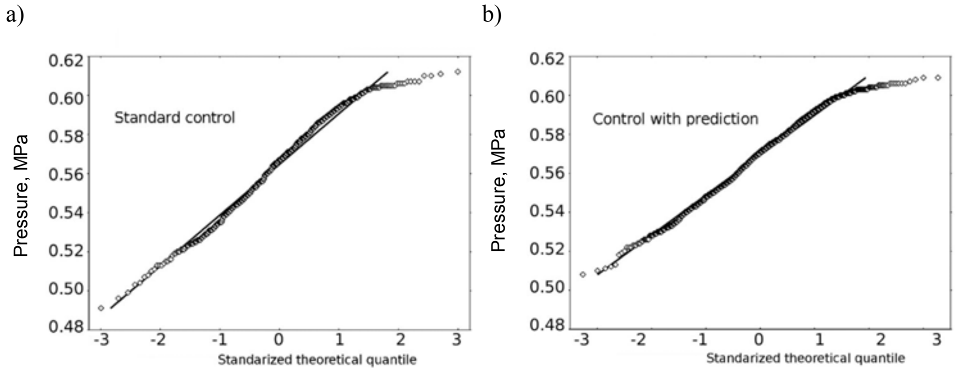

Fig. 3. Evaluation of conformity of compressed air pressure distribution to Gaussian distribution; a) process controlled by standard algorithm, b) process controlled by optimised algorithm

The goal of the analysis was comparison of the efficiency of two control algorithms. Because of similar nature of distribution unconformity for both analysed sets of data, the transformation of variables was neglected and estimation of process capability was made based on raw data (original measures).

Potential c_p and real c_{pk} process capability ratios were calculated using following formulas:

$$c_p = \frac{USL - LSL}{6\sigma} \tag{1}$$

$$c_{pl} = \frac{\mu - LSL}{3\sigma}\ ;\ c_{pu} = \frac{USL - \mu}{3\sigma} \tag{2}$$

$$c_{pk} = \min\left(c_{pl}, c_{pu}\right) \tag{3}$$

where: μ is mean value of analysed process variable, σ is standard deviation, c_{pl} and c_{pu} are lower and upper capability ratios accordingly. The results of computations as well as histograms for analysed data relative to specification limits were shown in Fig. 4.

a)
b)

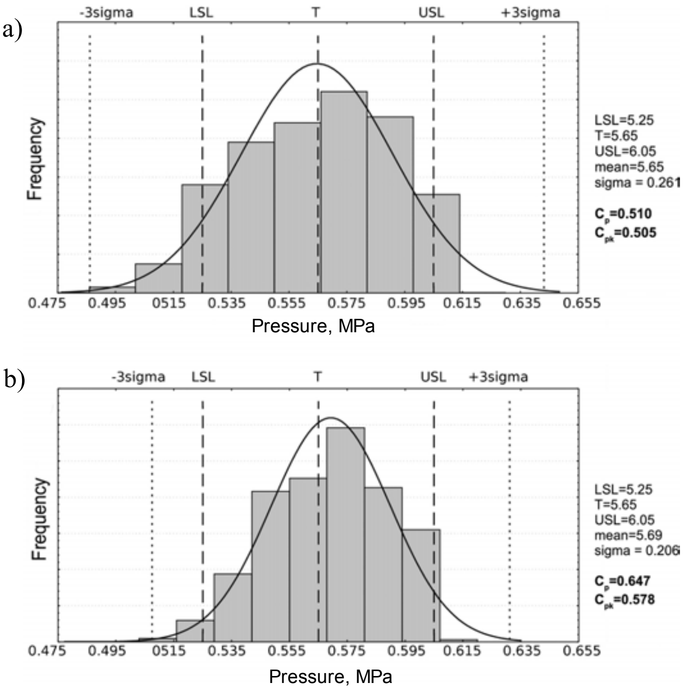

Fig. 4. Histogram and process capability ratios for quality characteristics (pressure of compressed air): a) process controlled by standard algorithm, b) process controlled by optimised algorithm

The process capability analysis made for process of compressed air production controlled by both tested algorithms proved higher efficiency of algorithm with prediction feature. Potential capability as well as real capability (c_p = 0.647, c_{pk} = 0.578) for the process controlled by improved algorithm are higher than corresponding values (c_p = 0.510, c_{pk} = 0.505) for process with standard algorithm (without prediction).

The autonomous control mode

Example time diagrams of the air pressure measured at the compressor plant exit point were shown in Fig. 5 and in Fig. 6. The compressor plant was working in the autonomous mode at the time of the data acquisition. During the period of time shown in Fig. 5 the air consumption was low and one compressor was enough to keep the air pressure between the control limits. The motor was switched on all the time (grey area below the graph) and the main valve was switched off periodically (white areas) to temporary stop pumping the air when the pressure reached the upper control limit. The compressor was pumping the air only in the periods -A, B-C, D-E and F-G, H- shown in Fig. 5. The lengths of the air pumping and idle periods depended on the actual load of the system (amount of air withdrawn from the air line by the activity in the manufacturing system). For example, in the period G-H (Fig. 5) the system load was increased (more air was taken from the network) and as a result, the compressor idle time was shortened. Upper and lower pressure limits drawn in the figures define the acceptable control area. An alarm was set if the actual pressure value went above the upper limit or below the lower limit.

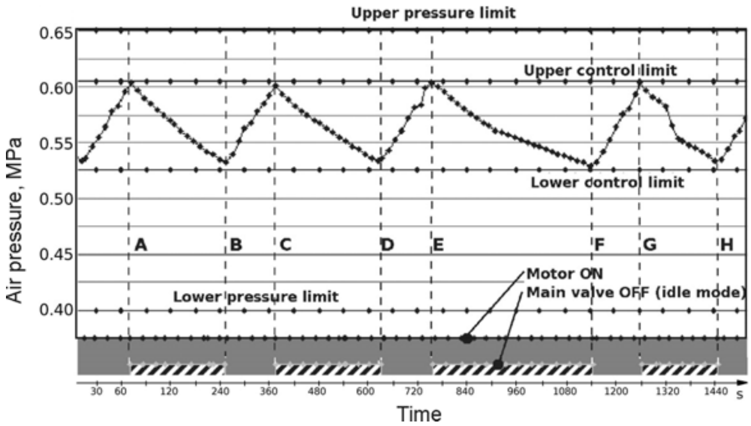

Fig. 5. Pressure in 0.6 MPa line at the compressor plant exit point during low air demand period (low activity on the shop floor)

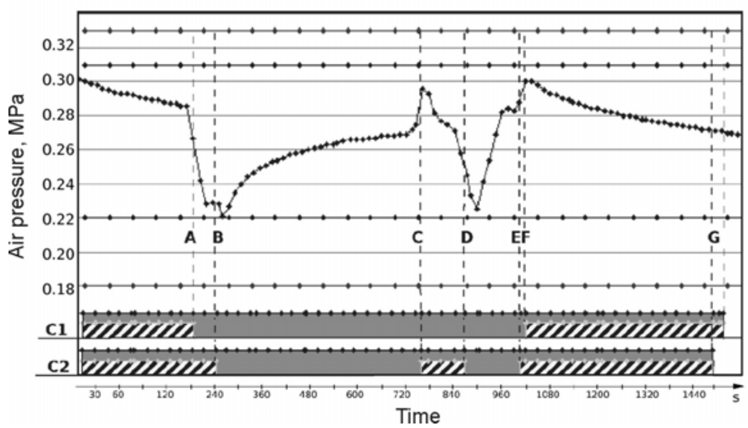

Fig. 6. Pressure in 0.3 MPa line at the compressor plant exit point during step air demand changes period (transportation of concrete and silo maintenance)

In Figure 6, the work of the 0.3 MPa compressor group under the high variable load conditions was illustrated. During the period of time shown in the graph, transportation and silo maintenance operations were performed. The load increased right before point A and remained high (but variable) until the moment marked with F. In the moment A, the system (control algorithm) reacted to the falling pressure with putting into work the compressor C1. As that was not enough to increase the pressure in the line, the compressor C2 was put to work in the moment B. In the moment C, a step increase in the pressure was detected and the control reacted with putting compressor C2 on idle. C2 was put to work again in the moment D when the pressure began to fall rapidly. The compressors C1 and C2 were put on idle again in the moments E and F when the load decrease was detected. After the maximum idle time had elapsed, the compressors were switched off. Here, the compressor C2 was working as an auxiliary machine and therefore it was switched off first.

Alarm condition handling was illustrated in Fig. 7. The compressor was switched off when the oil temperature went beyond the limit value. The compressor could be put to work again only after the oil temperature went below the limit again (and a certain amount of time elapsed). The event was logged for the operator to see and find the cause of the alarm but in the autonomous mode the compressor could not be switched off completely as it could lead to an unstable system. As it was observed during the system implementation phase insufficient cooling, especially during the summer months when the ambient air temperature was above 25°C, often caused the oil temperature alarms.

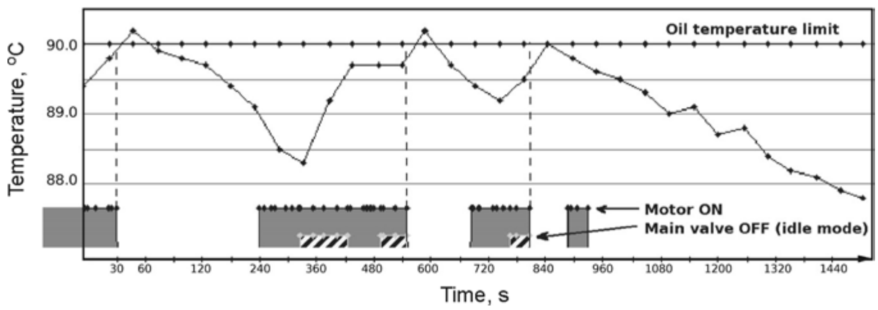

Fig. 7. Compressor switched off when a high oil temperature alarm appears (autonomous mode)

The effects of thermal overload of one of the compressors in the group are shown in Fig. 8. During the high air consumption period, one of the compressors had to be switched off from time to time because the oil temperature was rising above the limit. The first time a machine was put aside because thermal overload occurred in the moment right after moment B. Then, as the high air demand continued, the machine had to be switched off periodically for increasing time to cool down. The situation stabilised in the moment E when the air load decreased.

The output air pressure was varying rapidly during that time as the system production capacity was decreased.

Monitoring and process diagnostics

The values of all process variables and parameters were being archived on the hard disk drive mounted inside the operator's terminal. It was possible to browse through the archived data records in the same way as through the recent process history plots (similar to the plots shown in the Figures 5-8). During the system development and implementation time, it appeared that the operator did not feel comfortable with the classic control charts and he preferred to use simple time plots instead. The most important process variables used for machine and process diagnostics were:

- compressed air temperature at the output of each compressor,
- oil (lubricant) temperature in each compressor,
- oil pressure in each working compressor,
- air pressures in the 0.6 MPa and 0.3 MPa plant exit points.

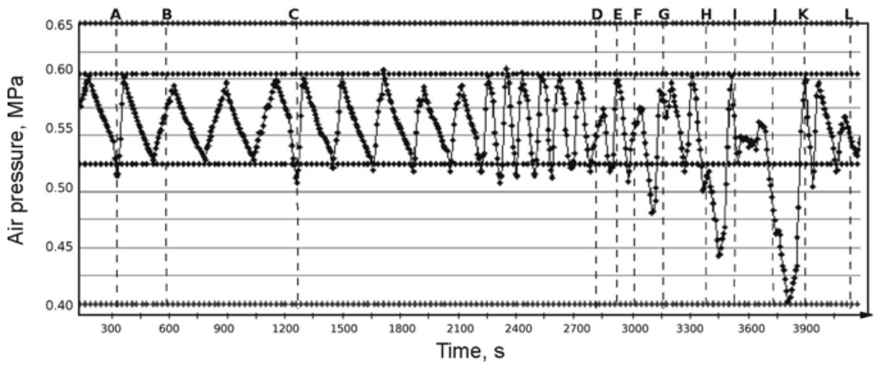

Fig. 8. Output pressure fluctuations as a result of thermal overload of one of the compressors

Additionally, the following binary signals were used for diagnostics:

- oil level in each compressor,
- coolant (water) level,
- 4-20 mA analogue line breakdown,
- motor state feedback signal (all motors).

One of the most obvious effects of the project was the decrease in the number of machine breakdowns and air pressure drop-downs. The system operator, armed with the simple diagnostic tools, could foresee problems before they appeared. As the actions such as machine maintenance stops could be planned at least a day ahead the operator was better prepared and usually could fix the problem at first try. The automated control system did not allow any machine to work beyond its normal work conditions, for example with high oil temperature or without the coolant, so the machine breakdowns due to overload did not happen any longer.

Summary

Implementation of the automated control system in the compressor plant resulted with a stabilisation of the production process and the decrease in the number of breakdowns. The compressor plant could work autonomously for long periods of time and the performance of the entire plant has risen. The machines that failed permanently during the unattended operation time were put down automatically to minimise the repair costs. The cause of the failure could be easily identified thanks to the process history records that could be easily accessed by the operator. After the implementation of the system the operator intervention was normally required once a day for process log analysis and machine maintenance. The operator was no longer involved in direct control actions and was not required to observe the output pressure gauges constantly.

The introduction of predictive action to the controller resulted with better control quality in both compressor groups. The pressure was kept within the control limits all the times except for the cases of extreme load changes, usually caused by some malfunction in the production floor. Further improvement of the process capability was unnecessary, as it would result in increased compressor switching frequency.

After the system was implemented the energy use ratio of the plant decreased because the unnecessary machines could be switched off automatically when the system load decreased. The process operator also recorded lower oil consumption.

References

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