Electric Motor Systems
Platform EMSA

Digitalisation in electric motor systems – Part II

Technical recommendations for industrial end-users

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The report was prepared under the Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E) – **Electric Motor Systems Platform** (EMSA).

This is the second in the series of four reports published in 2024 on the digitalisation of electric motor systems, elaborated by EMSA. The four publications:

- Digitalisation in electric motor systems – Part I: Findings for policy makers
- Digitalisation in electric motor systems – Part II: Technical recommendations for industrial end-users
- Digitalisation in electric motor systems – Part III: Catalogue of case studies
- Digitalisation in electric motor systems – Part IV: Energy consumption due to the digitalisation of electric motor systems

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Abstract:

This publication formulates technical recommendations for end-users on how to digitalise their motor systems. Firstly, there are general recommendations for the introduction of digitalisation in companies. Secondly, for pumping, ventilation and compressed air systems, more detailed recommendations were elaborated. These recommendations are based on interviews with end-users and system providers and on other results from EMSA's work on the topic of digitalisation of motor systems during the period 2021 – 2024.

About the 4E TCP Electric Motor Systems Platform (EMSA):

The goal of the Electric Motor Systems Platform EMSA is to increase energy efficiency and reduce greenhouse gas emissions worldwide by promoting highly efficient electric motor systems in the EMSA member countries, industrialised countries, emerging economies and developing countries. Electric motor systems consume about 10 700 TWh annually worldwide and were responsible for 53% of the global electric energy consumption in 2016. [1] This corresponds approximately to the combined electricity consumption of China, the European Union (28 countries) and the USA.

Further information on EMSA is available at: www.iea-4e.org/emsa

About the Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP):

The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP) has been supporting governments to coordinate effective energy efficiency policies since 2008. Fourteen countries and one region have joined together under the 4E TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions. The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.

Current members of 4E TCP are Australia, Austria, Canada, China, Denmark, European Commission, France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, UK and USA.

The main collaborative research and development activities under 4E include the

- Electric Motor Systems Platform (EMSA)
- Efficient, Demand Flexible Networked Appliances (EDNA) Platform
- Smart Sustainability in Lighting and Controls (SSLC) Platform
- Power Electronic Conversion Technology Platform (PECTA)

Further information on the 4E TCP is available from: www.iea-4e.org

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1 Executive summary

EMSA developed recommendations for the digitalisation of motor driven systems. Firstly, there are general recommendations for the introduction of digitalisation in companies. Secondly, for pumping, ventilation and compressed air systems, more detailed recommendations were elaborated. These recommendations are based on interviews with end-users and system providers, as described in chapter 2 of this report.

Through digitalisation, production and work processes can be simplified and streamlined. Energy efficiency is one of the many benefits of digitalisation of production and work processes in the business. Digitalisation can also create additional value, such as simplified monitoring of environmental parameters, predictability in processes and maintenance, introduction of more efficient control systems, and reduced emissions. Other benefits may include improved working conditions, quality traceability, increased access to information, and enhanced safety.

Targets and possibilities of digitalisation concerning energy and energy cost reduction found during the interviews include:

1. Requirement to report and achieve targets for water, energy and CO_2 consumption is often the trigger
2. Reduction of electricity consumption during non-production times; weekend shutdowns

Measures implemented include:

3. Switching off certain systems/air compressors and reducing compressed air pressure at the weekend, reducing idle hours
4. Reporting and analysis of energy effect of different operational parameter-setting
5. Automated leak detection in compressed air systems
6. Operation of chiller systems based on weather forecasts
7. Preventive maintenance of machines (detection of pressure fluctuations in pumps, wear monitoring for electric motors)
8. Condition monitoring of machines through vibration analysis
9. Load management of different machines to profit from low price periods or to avoid high price periods
10. Simulation of systems before they are actually installed (e.g. simulation of the energy requirements of the compressed air station when installing a more efficient compressor).

Many industries already have implemented digitalisation to some degree. In most industries, different parts of the business are digitalised, but they are not necessarily connected to each other.

Digitalisation aimed at achieving more efficient processes and work requires collecting data and information from the relevant processes/systems. The collected information needs to be analysed and interpreted to draw conclusions about potential actions that improve efficiency. There are many different techniques and tools that can be used.

Before starting with the digitalisation of motor driven systems, the most promising systems should be identified. There are different techniques for collecting data depending on its intended use. Data can be collected at specific intervals or in real-time, from individual machines as well as from a production line or an entire facility.

Data analysis involves transforming and processing collected data to visualise relationships and enable conclusions. The information can be used to design control signals to improve production. Large amounts of data from many sources increase the complexity of describing a system in a way that mathematical formulas often cannot. Combining concepts from traditional energy management systems, such as ISO 50001, with digital technology and software applications can provide new insights into consumption and usage patterns.

Concerning specific recommendations for motor driven systems the report covers pumping, ventilation and compressed air systems.

Pumping systems

Depending on the application and user requirements, several digitalisation options are available in the pump sector. Most options have been developed in the area of optimised maintenance and increased reliability, with energy efficiency as next area of interest. Since an emerging damage of the components of the whole drive system from motor to machine also leads to increased energy consumption, as well as operation outside the design load curve, these options are also relevant in this context.

Three types of pump monitoring technologies are described in the guide:

- Measuring the electrical power (current and voltage)
- Vibration and temperature sensoring
- Use of a Variable Speed Drive (VSD) as monitoring device.

Ventilation systems

For ventilation systems, the guide outlines digitalisation measures on the following levels:

1. Field level (sensors and actuators; connected directly or communicatively, e.g. via radio or bus systems).
2. Automation level: this contains the control devices (usually programmable microcomputers), including simple operation and signal processing, including logic and sequence controls.
3. Management level: the building management system (BMS) is located at the management level. This is the top level and is responsible for central control and the optimisation or control of operating sequences. It contains a visualisation interface on which statuses, results, statistics and evaluations can be displayed.

Compressed air systems

For compressed air systems, the following measurements are recommended and described in more detail:

- Measurement of electrical power
- Measuring the volume flow in the compressor station, in the distribution line and on machines
- Pressure measurement on compressors and in the network
- Temperature sensors in the room and directly at the in- and outlet of the compressor stage
- Bearing monitoring - vibration analysis
- Dew point measurement and measurement of compressed air quality

Furthermore, the difference between analog and digital sensors is described, and possibilities to transmit the data to different systems and their functions are shown.

2 Introduction

This publication is part of the IEA TCP 4E Electric Motor Systems Platform's (EMSA www.iea-4e.org/emsa) workstream "New Industrial Developments and Digitalisation in Motor Systems".

4E EMSA is a Technology Collaboration Programme (TCP) under the International Energy Agency involving 9 countries/regions. These are: Australia, Austria, Denmark, European Commission, Netherlands, New Zealand, Sweden, Switzerland, USA. The lead country is Switzerland. The aim of the cooperation is to support governments to design and implement effective policies for efficient electric motor systems. The fourth phase of the programme ran between 1 March 2019 and 28 February 2024.

Four countries have worked together on the topic of digitalisation in motor systems: Austria (lead), the Netherlands, Sweden and Switzerland.

Electric motor-driven pumps, fans and compressors are common technical equipment in many companies. Up to 80 percent of all electricity in the industry is used to drive electric motors. With the help of digital tools and techniques, it is possible to optimise energy usage and reduce electricity consumption in electric motor-driven systems.

Digitalisation is a buzzword and hence it is important to clarify what is meant by it. EMSA published a report on the *Classification of digitalisation technologies for electric motor driven systems* in 2022. Therein, an overview of the major digitalisation technologies that are used in the field of electric motor systems is provided (see Figure 1).

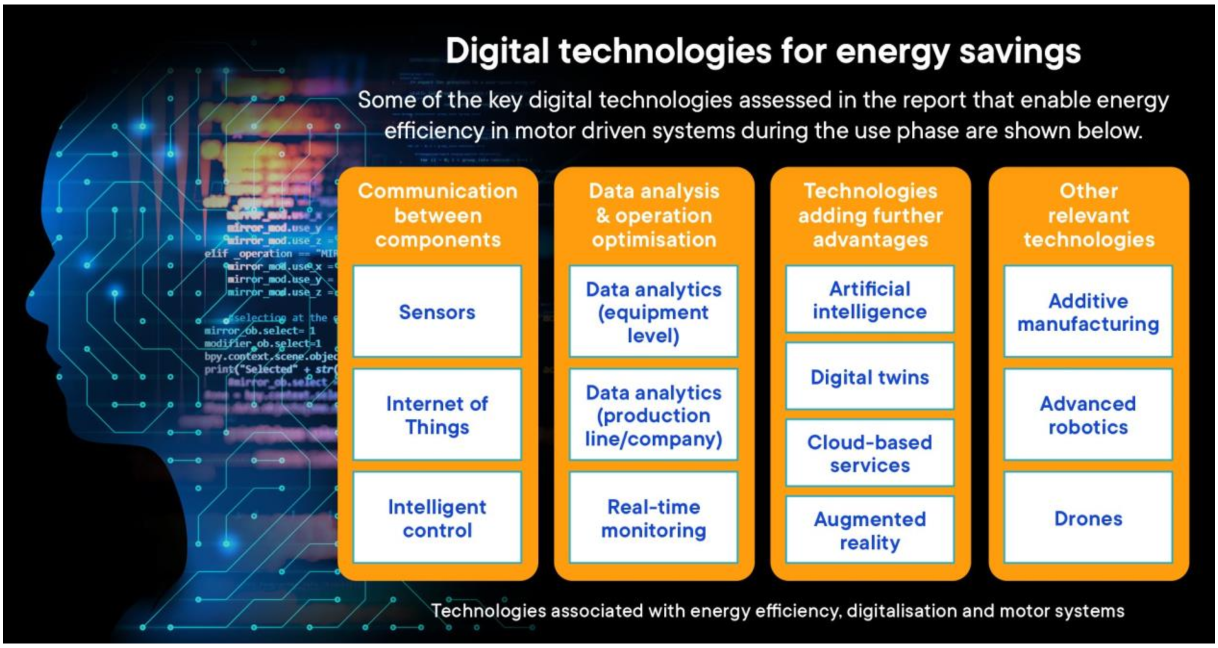

Figure 1 Digitalisation technologies analysed in the EMSA report Classification of digitalisation technologies for electric motor driven systems [1]

Digitalisation of motor systems creates transparency in terms of how energy is used as well as regarding operating parameters of the equipment. Digitalisation also enables advanced monitoring, providing targeted information that can be acted upon (manually or automated). This publication aims to help industrial end-users identify possibilities for that.

Sources of information

To gain a better understanding of the challenges and possible solutions the industries face concerning digitalisation, as well as to analyse how authorities can facilitate digitalisation, 18 interviews with manufacturing industries, suppliers of digitalisation solutions and energy consultancies have been carried out by CIT Industriell Energi AB in 2022 in Sweden, financed by the Swedish Energy Agency, and by the Austrian Energy Agency in Austria. Companies from the following sectors participated in the interviews: chemical industry, bearing and seal manufacturer, engineering company for special steels, manufacturer of gas engines, baby food manufacturer, cheese production, beverage manufacturer, forestry cooperative, motor manufacturer, digital service providers, electrification and automation provider, energy consultants, compressed air system providers. The results of these interviews formed the basis for the recommendations provided in Chapter 2.

Chapters 3 - 5 provide recommendations for digitalisation of pumping, compressed air and ventilation systems, based on interviews with system experts, series of case studies (see [21]) and researching data (webpage information).

3 General technical recommendations

Within the framework of EMSA's work on digitalisation, one action has been to investigate how digitalisation of electric motor systems could help improve energy efficiency of operations in industry. This chapter begins by describing the benefits that digitalisation technologies can bring to production companies and the solutions that are already helping companies to achieve various goals, particularly in terms of reducing their energy consumption or increasing their energy efficiency.

In the second sub-chapter some general recommendations and explanations are given for how to deal with digitalisation in companies.

3.1 Targets and possibilities of digitalisation

Through digitalisation, production and work processes can be simplified and streamlined. For example, digitalisation can highlight opportunities for synergies or potential risks of sub optimisation. Energy efficiency is one of the many benefits of digitalisation of production and work processes in the business. Digitalisation can also create additional value, such as simplified monitoring of environmental parameters, predictability in processes and maintenance, introduction of more efficient control systems, and reduced emissions. Other benefits may include improved working conditions, quality traceability, increased access to information, and enhanced safety, see Figure 2.

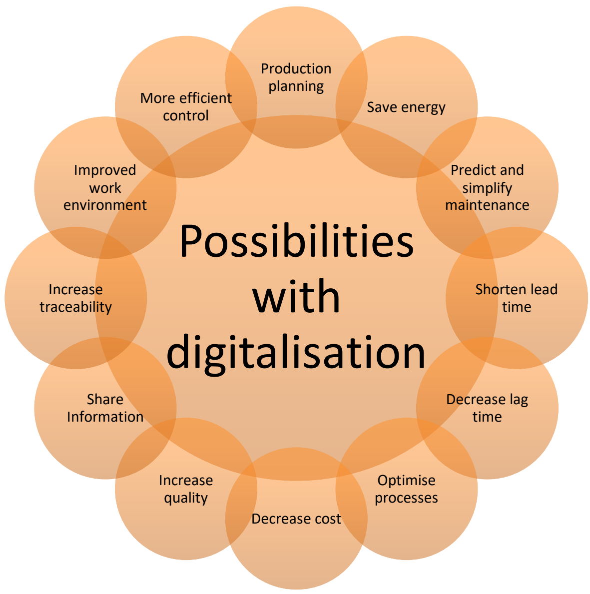

Figure 2 Digitalisation offers numerous opportunities for improvements, not only related to energy.

The added values of working with digitalisation cannot be separated from each other. Often, one action can create conditions to improve and/or streamline in multiple areas. In the long term, efforts in digitalisation can make the business better prepared to handle challenges in the future, such as changes in the market or new legislation. Based on the potential cost savings or incomes, increased production capacity, improved quality or better information management often show larger potentials than energy savings. Digitalisation should hence be seen as a cross functional process, that enables data for improved decision making. Successful implementation of digitalisation should therefore also take a wider perspective on the business processes and operation.

During the interviews conducted in Austria and Sweden, some companies stated that the requirement to report and achieve targets for water and energy consumption and CO_2 emissions is often the trigger for companies to invest in the digitalisation or electronic data collection of electrical energy and other media, such as steam, compressed air or hot water.

For example, for recording the CO_2 footprint of beverage packaging for beverage producers, key figures per kg or litre of product are important for sustainability management and reporting in the supply chain (energy consumption, i.e. gas and electricity, and water), which are compiled at company level. For this, all refrigeration systems, air compressors and ventilation systems are to be included in a central control system to record and document total energy consumption. Furthermore, the reporting and visualisation of such key figures leads to awareness-raising and thus prudent use of energy among employees.

Targets and possibilities of digitalisation concerning energy and energy cost reduction found during the interviews include:

11. Requirement to report and achieve targets for water, energy and CO_2 consumption is often the trigger
12. Reduction of electricity consumption during non-production times; weekend shutdowns

Measures implemented include:

13. Switching off certain systems/air compressors and reducing compressed air pressure at the weekend, reducing idle hours
14. Reporting and analysis of energy effect of different operational parameter-setting
15. Automated leak detection in compressed air systems
16. Operation of chiller systems based on weather forecasts
17. Preventive maintenance of machines (detection of pressure fluctuations in pumps, wear monitoring for electric motors)
18. Condition monitoring of machines through vibration analysis
19. Load management of different machines to profit from low price periods or to avoid high price periods
20. Simulation of systems before they are actually installed (e.g. simulation of the energy requirements of the compressed air station when installing a more efficient compressor).

3.2 General recommendations for digitalisation in industrial companies

Many industries already have implemented digitalisation to some degree. In most industries, different parts of the business are digitalised, but they are not necessarily connected to each other.

Digitalisation aimed at achieving more efficient processes and work requires collecting data and information from the relevant processes/systems. The collected information needs to be analysed and interpreted to draw conclusions about potential actions that improve efficiency. There are many different techniques and tools that can be used. In the following, some of the most central concepts are described clearly.

Firstly, digitalisation of a company should be a strategic decision supported by management and staff. Secondly, one has to deal with the different components involved on technical level. Thirdly, one of the most important targets of digitalisation, gaining transparency of the production process, is explained in more detail.

Before starting with the digitalisation of motor driven systems, the most promising systems should be identified.

3.2.1 Strategic decision

Implementing digitalisation in a business enables data on many different levels to be analysed for multiple purposes. The implementation includes hardware, data collection systems, data storage and management, training of staff and development of models and algorithms to support decision making. To make an implementation as successful as possible, it is therefore important to think through what decisions that could be made, which data these decisions would need, and how that data could be captured. The implementation of digitalisation therefore benefits from a strategic decision that covers all these steps.

A good starting point to raise efficiency in electric motor systems, is the analysis of one major energy consuming system; trying to save energy by digitalisation of this system which can be a showcase for the possibilities of digitalisation in a company.

3.2.2 Central components

A digital model of a physical system presupposes the conversion of physical, biological, or chemical values of the system into signals that can be read and digitally stored. This type of information about the system's properties and functions can be collected using sensors.

Sensors are fundamental for connecting objects to a digital infrastructure via networks. A collective term for this is the Internet of Things (IoT), which also includes data processing and user interfaces.

An infrastructure, such as a motor or a facility, requires a control system to function as planned. Conventional control systems are based on mathematical models where the variables to be controlled need to be known. Intelligent control systems can develop their own models to learn about processes, disturbances, and operating conditions to optimise performance.

3.2.3 Data collection and analysis

There are different techniques for collecting data depending on its intended use. Data can be collected at specific intervals or in real-time, from individual machines as well as from a production line or an entire facility.

Data analysis involves transforming and processing collected data to visualise relationships and enable conclusions. The information can be used to design control signals to improve production. Large amounts of data from many sources increase the complexity of describing a system in a way that mathematical formulas often cannot. Combining concepts from traditional energy management systems, such as ISO 50001, with digital technology and software applications can provide new insights into consumption and usage patterns.

Different functional areas in companies also have different interests in data collection: the controlling department is interested in which cost centre needs how much energy, the purchasing department is interested in a forecast of energy requirements for more favourable energy procurement, the energy manager is interested in precise energy measurement of consumers, the maintenance department is interested in data that enables predictive maintenance. It is therefore important to determine across departments which data or key figures are required, and which are relevant, by that, acceptance of data collection and evaluation increases, and the data is also used once the project has been implemented. To this end, the goals to be achieved must be defined: for example, CO_2 neutrality or 15-20% energy savings.

Not only electricity, but also steam, compressed air, water, demineralised water and technical gases should be considered for the systems to be recorded. It is then necessary to determine which are the most important, which Key Performance Indicators (KPIs) are to be recorded, which measurement structure is to be defined and which actual values are to be collected.

However, context is important when evaluating the data: a lower energy requirement can also be linked to a lower production figure or other factors. In order to determine relevant deviations, communication with many people is necessary. In general, it is therefore important to record the production status of the machine to determine whether production is actually taking place. The heating degree days are sufficient as a reference for buildings, but several parameters can be important in industry. This requires regression analyses and sometimes digital twins, which also make it possible to identify inefficiencies, as the actual value is compared with the model results and not a static value.

Companies should prepare monthly, sometimes weekly, reports on energy consumption. The visualisation of these key figures raises awareness among employees. In general, companies should set up monitoring of their main energy consumers. By displaying the energy consumption of the respective plant or line, production managers also become responsible not only for the output but also for the amount of energy required for it. This leads to more efficient processes in the long term and the display creates transparency as to which line is the most efficient and why.

For energy efficiency, more detailed data with a greater temporal recording of electricity consumption is required than is the case with conventional electricity meters; digitalisation, e.g. through smart meters, can help here.

When procuring machines, electrical energy measurement, air volume measurement and other relevant measurements that can be read out via OPC UA protocol should be required.

3.3 Which steps to follow for optimising electric motor systems?

If a company wants to digialise the electric motor systems, the following steps should be taken to make the best use of the resources required and start with the most promising systems:

Motor list

First, a list of the existing electric motor systems within the company should be created including a series of key data per system e.g. operating cost, electric load [kW], operating hours, redundancy, etc. This is necessary to detect the most relevant systems. These can be systems so far not identified as main energy consumers, e.g. pumping, compressed air or fan systems. Before starting the data collection, it is recommended to check the information already available within the company, e.g. from the energy management system, maintenance information, ERP/SAP system.

The first step in data collection is to carry out a rough analysis of the existing data referring to electric motor driven systems. Therefore, the general data should be collected for each motor, for example in an Excel spreadsheet, including data on the driven application e.g. pump, fan, compressor, other.

Although technology-specific data collection is the focus of the second step, it may be useful to collect already at this first step all data on the motor nameplate: enclosure type, mounting configuration, voltage rating, full-load amps and full load efficiency (if no rating is present, then the energy efficiency class of the motor corresponds to IE1 or IE0).

Selection for more detailed analysis

The next step is, first, to rank the motors according to energy consumption (note: in most cases this will be a calculated value) and, second, to select old motors with high energy consumption without load control (for pump, fan, compressor) for a more detailed analysis.

Furthermore, for existing systems the equipment with sensors or digital solution should be checked.

At the end of this step, those systems should be identified for which important data is missing or for which data could be useful to optimise the operation or maintenance with aid of digital solutions.

For the systems with high priority, the following steps should be taken:

1. Make an analysis of the entire electric motor system (e.g. motor, pump, pipe system with valves and possible restrictions). There may be efficiency gains to find in other equipment than just the motor.
2. Start the process (with those old motors selected ready for replacement) by dimensioning motors that match the needs of the processes. Evaluate load profiles in normal operation, can a smaller motor accomplish the same work that the current motor does, and does the control match the demand – or is an adapted control needed? This can be detected by digital solutions.
3. Measure a motor (digitally) over time and decide if there is a need for a Variable Speed Drive (VSD) or not. A motor that runs at full speed all the time can benefit from not having a VSD.
4. Collect and use motor data for follow up or real time analysis.
5. Make individual business case (assessment of economics) and decide on investment
6. Define strategic purchase policy that corresponds to Ecodesign requirements and Minimum Energy Performance Standards (MEPS).
7. Additional effects that could be achieved through digitalisation are:
    a. Smarter control and planning
    b. Balance start and stop when there is no process need with the extra wear start and stop cause to the motor.
    c. Data analysis of loads, active and reactive power, vibrations, temperature etc. followed by corresponding control.
    d. FDD, Fault Detection and Diagnosis.

4 Digitalisation of pumping systems

Depending on the application and user requirements, several digitalisation options are available in the pump sector. Most options have been developed in the area of optimised maintenance and increased reliability, with energy efficiency as next area of interest. Since an emerging damage of the components of the whole drive system from motor to machine also leads to increased energy consumption, as well as operation outside the design load curve, these are also described here.

Three types of pump monitoring technologies are described:

1. Measuring the electrical power (current and voltage),
2. Vibration and temperature sensoring,
3. Use of a Variable Speed Drive (VSD) as monitoring device (standalone or in combination with sensors).

4.1 Measuring the electrical power (current and voltage)

By measuring the electrical power (current and voltage) of the motor of a pump, the following findings can be obtained from the course of the active power, regardless of voltage fluctuations and load (which would be the case if only current were considered):

a. Running time of the machine
b. Actual power consumed (in relation to the rated power of the installed motor and the design of the pump), over time
c. Number of starts and stops (switching cycles)
d. Recognition of normal operation without faults (e.g. power consumption, flow, pressure) over the course of time
e. Permanent online monitoring and analysis of the electrical parameters, the operating parameters (flow, pressure) and therefore the calculated efficiency of the pump
f. Comparison of the operating point with the manufacturer's pump characteristic curve
g. Alarm if inefficiencies occur during pump operation
h. Detection of air bubbles due to constantly increased load demand
i. Detection of contamination, changes in the viscosity of the liquid or corrosion of the pump due to increasing load demand over time
j. Detection of dry running due to greatly reduced load profile
k. Detection of a blockage due to an initially sharply increasing, then decreasing load curve
l. Monitoring and diagnosis of motors for overload, underload and function
m. Emergency shutdown of the motor if a switching threshold is exceeded or undershot
n. Recognition of voltage and current asymmetry in the power supply
o. Recognition of harmonic distortion

Ready-to-install control cabinet solutions with touch panel and monitoring display are already on the market from manufacturers for these measurements. [2,3,4,5]

Sensors for current and voltage measurement do not have to be installed near the actual machine, but near the power supply. The measured active power can be recorded and evaluated linearly over the entire load range, whereas pure current measurement (ammeter) is inaccurate in the lower load range.

The motor data can then be transferred to a higher-level control system, a database or the cloud via Modbus TCP (Transmission Control Protocol), Open Platform Communications Unified Architecture (OPC UA), Profinet or Profibus, for example.

Pump efficiency reports can then be created and displayed on the end devices for visualisation according to user specifications and dashboards. Some providers also include savings potential calculations here. [5]

Special providers have also developed methods that can obtain even more detailed information from the analysis of voltage and current. Small changes in the operation of pumps, such as unusual vibrations, also have an effect on the magnetic field of the connected electric motor, which in turn affects the supply voltage and current. By analysing the current and voltage, power and motor speed using various methods (electrical signal analysis, e.g. fast Fourier transform (FTT)), a variety of other mechanical and electrical faults and deviations from the pump's optimum operating point can be detected [3]:

a. Pump cavitation
b. Gearbox damage
c. Motor bearing damage
d. Motor stator windings
e. Automatic classification of the operating point.

Some providers also enable the creation of a digital twin to process current data on operating status, performance and deviations, and self-learning alarm thresholds can also be created.

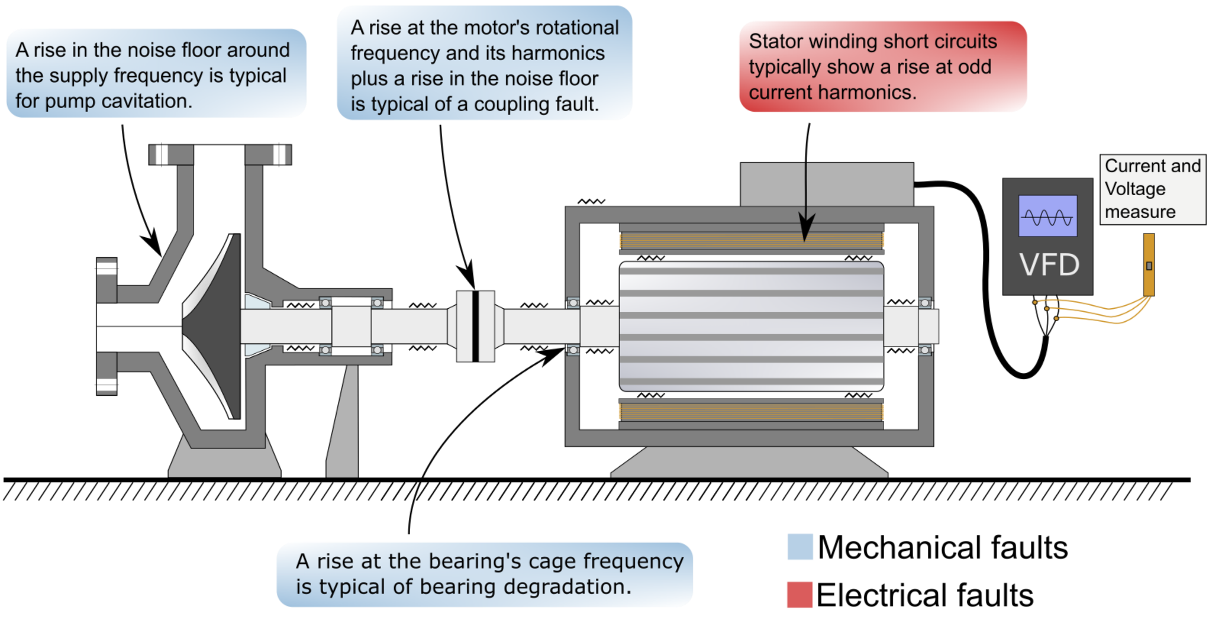

Figure 3 Options for detecting pump and motor malfunctions through current and voltage analysis (Austrian Energy Agency based on Samotics 2024 [3])

4.2 Vibration, temperature and pressure sensors

Pump suppliers offer other, less expensive pump monitoring methods that focus primarily on failure prevention and condition monitoring. Monitoring is carried out using acceleration and temperature sensors that are glued to the outside of the pump or attached with magnets. They transmit the data recorded every hour to the cloud via the transmitter unit, gateway and mobile network, where it is analysed using frequency analysis, for example, and can be accessed via mobile devices. The pump data must first be entered. The advantages are [6,7]:

a. Monitoring of the pump's vibration and temperature values
b. Operating hours
c. Load status (of uncontrolled pumps)
d. Early detection of damage
e. Misalignment of the pump and motor.

The aforementioned pump monitoring systems can also be equipped with their own sensors for recording bearing and machine vibrations, which monitor and pre-evaluate this data and thus detect cavitation and incipient bearing wear at an early stage.

Suppliers of circulation pumps also offer a function for calculating the transferred thermal energy; an analog interface to external sensors for the flow and return temperature is integrated for this purpose. The flow rate is calculated using the power consumed and the respective pump curve. The transferred heat energy is then calculated from the above data. [8]

Monitoring the operation of a pump can also be done with the help of an intelligent pressure gauge. The device has two pressure sensors and records the pump's load profile to identify any optimisation potential for improving energy efficiency and availability.

4.3 Use of suitable Variable Speed Drives

Variable Speed Drives can also fulfil many of these functions and offer intelligent control options. When using VSDs for pump control, the speed of the pump and thus the volume flow is regulated via the frequency, for example to maintain a constant system pressure. This is done via an external pressure sensor, and energy is saved by adjusting the volume flow. Pressure surges can be avoided by gently raising and lowering the pump.

Operation is via Bluetooth connection with a smartphone or tablet. An app can be used to monitor the pump's operating parameters, call up statistics on energy consumption and check the alarm history. Examples of other adjustable functions for some VSDs for pump operation are [9, 10, 11]:

a. Zero volume switch-off leads to energy savings by activating sleep mode; the pump is then switched on as soon as the pressure in the system drops
b. Dry-running protection of the water pump by detecting pump operation without back pressure
c. Adjustable overpressure and underpressure monitoring, detection of pressure sensor defects
d. Intelligent control of multi-pump systems
e. By measuring the speed (via the frequency) and power (voltage, current) and a stored pump characteristic curve, so-called sensorless pump control can be achieved without a flow and pressure sensor, as the measured values correspond to the delivery head and the delivery volume on the pump characteristic curve. For example,

the heating and cooling demand is derived from the hydraulic system resistance and the pump speed is then adjusted to cover the demand, thereby saving energy.

5 Digitalisation of ventilation systems

Some measuring points are normally present in every ventilation or fan system. In particular, pressure and temperature sensors are very often already installed in ventilation systems; in some cases, control is also based on other parameters, e.g. dust pollution in the exhaust air, or via motion sensors.

In industrial plants, it is first necessary to check the current status of control or digitalisation for the most important systems and whether and how possible evaluations are carried out.

In some cases, systems are switched on and off manually at a local level, in others the control is centralised and fully automated and the motors are equipped with Variable Speed Drives to optimise the operating energy. In some cases, systems from production are already connected to the building management system (BMS), where a lot of data is collected and monitored centrally. [18]

From this data, it is already possible to draw conclusions about the current situation of the systems and identify possible optimisation measures (e.g. optimum position of the exhaust air flaps and mixing flaps in recirculation mode). Here it is necessary to check whether it is also possible to calculate and monitor meaningful energy indicators.

In some cases, volume flow measurements are carried out temporarily or are permanently installed. Various measuring principles with different characteristics and accuracies can be used for this purpose. The most important types are thermal probes or hot-wire anemometers, vane anemometers and the Prandtl pitot tube. The accuracy of the measurement depends on the measuring principle, the dimensioning and, particularly in ventilation systems, the installation situation. For example, there are also areas in ducts where air flows through parts of the duct in the opposite direction.

In many cases (e.g. systems from 10 000 m^3/h), it makes sense to retrofit stationary volumetric flow measurements, whereby professional measurement is particularly important for short inlet sections (shorter than five times the diameter). The electrical power consumption of the fan motor must also be recorded.

The energy consumption of the entire system and/or the energy content of the air can be determined by means of heat and cooling meters and/or suitably positioned air energy meters and enthalpy sensors (in the outside air and supply air, if necessary also between the treatment stages of the air conditioning system). This enables many applications:

a. Precise heat and cold quantity determination per air line
b. Performance monitoring
c. Monitoring of the operating point of the fan or utilisation
d. Monitoring of the heating and cooling coils
e. Allocation of real costs to cost centres and tenants
f. Checking and monitoring heat recovery (in terms of performance, efficiency, yield, etc.)
g. Checking the control dampers

Technically, this is done by connecting the sensors (temperature and volume flow sensors) with the control or evaluation software. This process is called building automation (BA) or domotics and refers to the entirety of monitoring, control, regulation and optimisation of equipment in buildings. Building automation is divided into three levels:

4. Field level (sensors and actuators; connected directly or communicatively, e.g. via radio or bus systems).
5. Automation level: this contains the control devices (usually programmable microcomputers), including simple operation and signal processing, including logic and sequence controls.
6. Management level. The building management system (BMS) is located at the management level. This is the top level and is responsible for central control and the optimisation or control of operating sequences. It contains a visualisation interface on which statuses, results, statistics and evaluations can be displayed.

5.1 Field level: analog and digital sensors and data transmission

The field devices (sensors and actuators) record information (e.g. motion detectors, temperature sensors) and send it to the actuators. These convert the received data into switching signals, for example for the lighting, heating, air conditioning and ventilation system.

Analog sensors (pressure, flow, vibration, temperature, current/voltage measuring devices) output an analog measuring signal, i.e. a current or voltage signal proportional to the measured variable (4 to 20 mA). They therefore have a current/voltage output. Such sensors require external components such as an ADC (analog-to-digital converter) to convert the analog signal into a digital one. Digital sensors have a digital interface and transmit these, for example, via a serial or parallel bus (dew point, humidity, temperature in air conditioning systems).

Depending on the type of sensor, the data can be transmitted either wired or wirelessly. Analog data is transmitted via power cables. Digital transmission takes place using Modbus TCP/IP address via Ethernet, BACnet, Profibus or OPC-UA, for example. Another option is to transmit the data wirelessly via WLAN, Bluetooth or LoRaWan. Analog sensors require ADCs in any case.

The data can be transmitted directly or via different interfaces to:

a. Data logger
b. Controller (automation level)
c. Energy management software (management level)
d. Building management system (management level)
e. Cloud.

Data loggers with a screen on site can fulfil the following functions, for example:

a. Connection of several sensors (up to twelve) via different inputs, (Remote Terminal Unit (RTU=, analog, etc.)
b. Display of measured values and trends on the screen
c. Monitoring by setting alarms
d. Calculation of key figures (EUR/m^3, kWh/m^3)
e. Connection to the web
f. Reading out the data
g. Creation of reports.

5.2 Automation level: control

The automation level controls and regulates the system based on the data supplied by the field level and the specifications from the management level. So-called controllers take over the control of the Variable Speed Drives of the main drives as a speed specification via the voltage or via the humidity and temperature control, but can also take place via pressure, differential pressure, air speed or CO_2 sensors. The controllers also control the heating and cooling water pumps as well as the valves for delivering the heating and cooling water to the heating and cooling coils within the ventilation system, based on the data measured by the temperature sensors. The heating curves are also stored there. The controllers can then send the data to the BMS via various interfaces. The timer programme can also be set here for certain applications.

Many energy-relevant systems also have a Variable Speed Drive, for example, which can control the systems depending on the pressure and/or temperature, for example by means of a timer (with the option of programming a time programme) or by specifying external setpoints as control variables (e.g. pressure at the end of the supply line, volume flow specifications, temperatures).

In general, it is possible to automatically read out measured or calculated data from the Variable Speed Drive. Examples of this are the measured pressure or volume flows. However, it actually depends on the manufacturer whether such an interface can be made possible. It should also be noted that these data or interfaces can change with software updates.

At component level, however, fan manufacturers have recently developed motors and Variable Speed Drives for fans that can record, transmit and display a variety of measured values. Examples of this are:

a. Display of speed, status, voltage, current, power
b. Display of trends of these values
c. Display of the operating status, error displays
d. Vibration measurement of all three axes
e. Measurement and display of acceleration and deceleration time
f. Monitoring of cooling conditions (e.g. soiling of the fan housing and motor), vibration and operating hours (e.g. load profile)
g. Measurement of the temperature of the transistor

This data also enables predictive maintenance in order to determine the remaining service life depending on the running time and ambient conditions, to detect vibration and overheating and thus prevent failures. Connectivity is via Modbus or Bluetooth, which also allows the fan to be controlled via smartphone or tablet. The data is accessed via a cloud solution. [19]

In this context, some manufacturers also offer the option of sensorless control for forward-curved centrifugal impellers without direct measurement of the volume flow and the associated measurement uncertainty in the low utilisation range. In this case, the operating point is clearly determined via the motor current and the speed of the Variable Speed Drive as well as via the fan characteristic curve and the fan is controlled using only this data. [20]

5.3 Management level: monitoring

The operation and visualisation of the processes as well as the reporting of malfunctions take place at the BAS-management level. The data on building automation and system operation is collected centrally, visualised, evaluated and monitored. These include, for example, the percentage control of the fan (depending on the frequency of the Variable Speed Drive), the current pressure increase caused by the fans in the exhaust and supply air lines, the percentage position of flaps, the percentage opening of the mixing valves for heating and cooling registers as well as the temperatures in the supply and exhaust air line. Furthermore, the setpoints for heating and cooling operation in °C, pressure setpoints in the supply and exhaust air lines for the different operating modes can be stored and displayed and the time programme can be changed.

In addition, in modern BMS systems, cross-system control and optimisation algorithms can calculate specifications for the control and communicate them to the automation level.

With an energy data management system, the following data can be observed at this level with suitable equipment and connection of sensors or linking to other data sources:

a. Air generated over time [m^3/h]
b. Current operating pressure and over time
c. Electrical power consumed by the system over time
d. Specific energy consumption over time [$kW/m^3/h$]
e. Overview of all energy consumers (e.g. systems, lines, cost centres) over time periods (shifts, calendar days, hours)
f. Share of e.g. the ventilation systems in total power requirements and in power consumption during non-operational times
g. Total consumption [m^3] per calendar week, power consumption per calendar week [kWh]
h. Linking energy consumption to the ambient and operating conditions (ambient temperature and humidity, number of pieces produced)
i. Analysis of specific consumption (e.g. total electricity consumption per unit per week)
j. Heat used from heat recovery.

A data cloud also enables data transfer to external parties (or internal companies, for example in global companies), so that the analysis (historical data, trend development, predictive error detection) can be deepened or remote maintenance can be planned.

6 Digitalisation of compressed air systems

The following measuring points should be present in compressed air systems. Modern air compressor stations have energy management software functions built in, and partly already have some of these measurement points installed.

6.1 Measurement of electrical power

Monitoring the electrical power of compressed air systems has the following advantages:

a. Knowledge of the actual power consumption as a function of time, so that the dependence of the power requirement for compressed air on operating parameters can be displayed and analysed (e.g. number of active workstations, day of the week, time of day, number of units produced, etc.)
b. Knowledge of the power requirement for compressed air under typical operating conditions
c. Rapid recognition of situations with unusual, increased power requirements
d. Recognise faults: e.g. defective intake valve, which leads to increased power consumption at full load volume flow, or defective drive between motor and compressor element
e. Detection of other faults via the option of defining thresholds for the ampere value for the respective load states. Examples of this are:
    i. Minimum value for load run to detect faults such as belt breakage, signal fault or defective intake regulator
    ii. Maximum value for idling to detect unwanted load running
    iii. Maximum value for standby to detect incorrect wiring

For a stationary, permanent measurement, a three-phase power measurement is generally recommended for compressors with an output of approx. 55 kW or more, which measures current and voltage. The active, apparent and reactive power and cos phi can be determined on the basis of these values.

With the more cost-effective single-phase ampere measurement, the recorded power is calculated with fixed values for the possibly fluctuating voltage and with the variable power factor (cos phi) depending on the motor and load. This inaccuracy can be accepted for smaller compressors and is sufficient for a pure energy evaluation in many cases. At low loads, however, very low power factors can occur, and the power calculation can therefore lead to an incorrect result. [12]

The measurement should be installed at the central control cabinet of the compressor station. Either the power consumption of one or more compressors is measured or the power requirement of the entire compressed air station, i.e. including dryers, fans or any cooling water pumps. This total requirement should be measured, especially for stations with higher output and higher operating hours. [13]

The specific compressed air index in [kWh/m3] can already be calculated by measuring the power consumption and used to compare the different compressors and to evaluate the entire compressor station. However, the amount of compressed air produced is calculated using the electrical power consumed by the respective compressor and not measured separately.

6.2 Measuring the volume flow in the compressor station, in the distribution line and on machines

Measuring the volume flow can help to optimise the operation of compressed air systems. This can be done with a short-time measurement, but for bigger stations should be done on a continuous basis. It can be used for the following applications:

a. Evaluating the efficiency of the compressor or the control strategy, e.g. [kWh/m3]
b. Allocation of compressed air consumption to departments, lines, consumers, machines or for individual products
c. Detection of increased compressed air consumption (e.g. defective nozzles, incorrectly fitted hoses)
d. Leakage detection
e. Cost allocation to cost centers.

To measure compressed air consumption (flow, e.g. m3/s), a flow measurement suitable for the purpose is required. Depending on the desired application, this can be used in the compressed air station, in distribution lines or in individual machines. Normally, a thermal flow sensor is installed after the compressed air preparation, which is particularly suitable for dry, clean and not too hot compressed air. Many companies monitor the total volume flow delivered by the compressed air station, even on non-operating days, for example. On individual machines, the measurement can help to find leaks quickly. Here, monitoring can also be used to optimise maintenance, as increased compressed air consumption can also indicate other problems.

In particular, if a performance verification of the compressor is required, the measurement can also be carried out directly after the compressor in the main line (i.e. before the compressed air drying but after the water separator) using a differential pressure sensor that is suitable for wet compressed air and high temperatures, whereby pressure and temperature should also be measured. The accuracy of the measurement varies depending on the measuring principle and the actual measuring range. For such a measurement, a protocol or standard should be agreed upon, including the accuracy of the measurements and calculations.

The compressed air consumption is then recorded, for example, using a data logger on site, in other systems or directly in the cloud.

By simultaneously measuring the power consumption and the delivery volume of the compressor, it is possible to determine the specific output of the compressor in [kWh/m3] and thus monitor how much energy is required to produce one cubic meter of compressed air. This value depends on the efficiency of the compressor at the load point, i.e. the volume flow and pressure currently being generated. If several compressors are measured, the value also depends on which compressors are currently producing compressed air and how the control strategy is implemented. [14]

6.3 Pressure measurement on compressors and in the network

Pressure measurements make it possible to monitor the pressure from the compressor to the systems and are often already installed at various points to ensure proper operation of the entire system. New controls can regulate not only to the compressor discharge pressure, but also to the pressure at the end of the line or an average value thereof. However, pressure measurement can also be used to detect planned pressure drops and thus the need for higher pressure requirements on the compressors; for example, filters can be automatically monitored by differential pressure measurement. Pressure monitoring allows the pressure setpoint on the compressor to be kept as low as possible. [12]

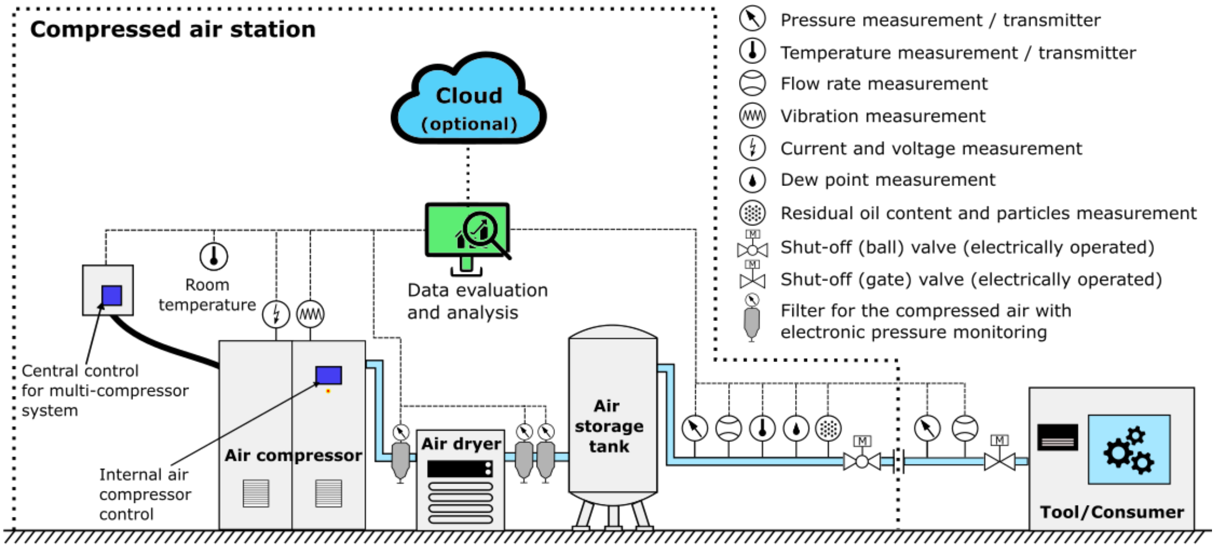

Figure 4 Overview of possible measuring points for the digitalisation of compressed air systems (Austrian Energy Agency)

6.4 Temperature sensors in the room and directly at the in- and outlet of the compressor stage

The room temperature and/or the air-inlet temperature of the compressor room should be monitored, as excessively high temperatures reduce the efficiency of compressed air generation. This can be caused by poor ventilation or insufficient cooling. [13]

Normally, a compressor is monitored via the temperature at the outlet of the compressor stage. However, access to this temperature is manufacturer-specific and directly linked to the internal control system, which switches off the compressor at very high temperatures (e.g. 120 °C).

A separate sensor optionally enables the temperature to be monitored externally and an ongoing increase to be detected. This is important, for example, to ensure that the compressed air temperature does not exceed the maximum dryer inlet temperature. Causes of increased temperature can be: unsuitable cooling due to poor ventilation of the compressor room, dirty coolers and filters or defective fans. Alternatively, the cooling water outlet temperature can be monitored for oil-free compressors. [12]

6.5 Bearing monitoring - vibration analysis

The service life of screw compressors depends heavily on their operating conditions, e.g. whether they are used as peak load compressors or base load compressors. Bearing damage increases the vibration frequency. Vibration sensors on the bearing of the compressor element enable early detection of bearing damage via online monitoring of the vibration speed. The operator is then informed if the adjustable warning threshold is exceeded. [12]

6.6 Analog and digital sensors

Analog sensors (pressure, flow, vibration, temperature, current/voltage measuring devices) output an analog measuring signal, i.e. a current or voltage signal proportional to the measured variable (4-20 mA). They therefore have a current/voltage output. Such sensors require external components such as an ADC (analog-to-digital converter) to convert the analog signal into a digital one. Digital sensors with a digital interface use, for example, a serial or parallel bus (dew point, humidity, temperature in air conditioning systems). [14, 15]

6.7 Dew point measurement and measurement of compressed air quality

Moisture content, residual oil content and particle measurements are used to monitor compressed air quality in several industries (e.g. pharmaceutical or food industry), especially for compressors that do not compress oil-free. Alarms can be used to alert operators to the need for maintenance work on the compressed air treatment system (dryer and filter). Oil, water and particles are then prevented from entering the compressed air network, the risk of contamination of end products is reduced and process reliability and pneumatic components are protected. [14]

6.8 Data transmission

Depending on the sensors, data is transmitted by cable (analog: power cable; digital: for example Modbus TCP/IP address via Ethernet, Modbus RTU, Modbus ASC II or RS485, Profibus and so on). RS485 enables data transmission over very long distances, for example 1,500 m. Using a Local Area Network (LAN) connection or Ethernet, data transmission over a distance of around 100 m is possible. [15]

Another option is to transmit data wirelessly via Wireless Local Area Network (WLAN), Bluetooth, Long Range Wide Area Network (LoRaWan). Analog sensors require ADCs for this. Another option is to transmit GSM transmitters directly to the network or the cloud; this is then implemented if access to the network is restricted.

The data can therefore be transmitted directly or via different interfaces to different systems:

1. Internal control of the compressor
2. Data logger (e.g. also as intermediate storage) in the compressor room
3. Industrial platform (for whole company)
4. Energy management software (for whole company)
5. Building management system (for whole industrial site)
6. Cloud (specific for compressor provider)

The possible functions for some systems are described below.

6.8.1 Internal control

Many energy-relevant systems have an internal control system that regulates the systems depending on the pressure and/or temperature, for example. These cannot be retrofitted. For example, air compressors are already controlled internally at this level in such a way that the calculated energy consumption represents an optimum of switching and control losses and the system is switched on and off depending on the consumption curve. Other functions include [16]:

a. Timer (possibility to program a time programme)

b. Specification of external setpoints as control variables (e.g. pressure at the end of the supply line, process variables)
c. Speed specification (serial, manual, external)
d. Various control variants and continuous control.

In general, it is possible to automatically read out measured or calculated data from the controls of compressed air systems. Examples of this are measured pressures and temperatures or calculated volume flows. However, it depends on the manufacturer whether such an interface can be made possible. It should also be noted that these data or interfaces can change with software updates.

6.8.2 Higher-level control on site

Depending on the manufacturer and the desired function, higher-level control systems for air compressors can perform the following tasks [12, 16]:

a. Higher-level control of e.g. up to 16 compressors (selection of the optimum combination of compressors) based on trend detection
b. Adaptation of the compressed air requirement of the entire station from several compressors to demand, taking efficiency into account (e.g. control losses of compressors with a Variable Speed Drive, switching losses (load, idle) of rigid compressors, and acceptable pressure fluctuations)
c. Display and storage of measured values (pressure, power consumption) for each compressor
d. Creation of energy and compressed air balances
e. Operating status monitoring, alarms
f. Display of overall diagrams for important measured values
g. Display and logging of the number of motor starts and the number of load-idle switching operations
h. Monitoring of many other data (vibration, compressed air temperature, refrigerant dryer, etc.)
i. Various software or hardware interfaces to building automation systems or energy management software, e.g. OPC UA, Unified Serial Bus (USB)
j. Link to cloud services (e.g. predictive maintenance, remote maintenance).

6.8.3 On-site data logger function

a. Connection of several sensors (e.g. up to 12) via different inputs (RTU, analog, etc.)
b. Display of measured values and trends on screen
c. Monitoring by setting alarms
d. Calculation of key figures (EUR/m³, kWh/m³, total consumption of individual lines, etc.)
e. Connection to web.

6.8.4 Energy management software function [17]

a. Compressed air generated in [m³/h] over time
b. Current operating pressure and over time
c. Power consumed by the compressed air system over time
d. Specific energy consumption over time [kW/m³/h]
e. Overview of all energy consumers (e.g. systems, lines, cost centres) over time periods (shifts, calendar days, hours)

f. Share of e.g. compressed air in total electricity consumption, in electricity consumption during non-operating time
g. Total compressed air consumption [m³] per calendar week, power consumption per calendar week [kWh]
h. Leakage detection
i. Linking energy consumption with ambient and operating conditions (ambient temperature and humidity, units produced)
j. Analysis of specific consumption (e.g. total electricity consumption per unit per week)
k. Heat used - heat recovery.

6.8.5 Cloud function

a. Data transfer to external parties (or internally for global companies, for example)
b. Analysis of this data (analysis of historical data, trend development, predictive fault detection)
c. Remote maintenance
d. Energy management via cloud.

Benefits of optimising compressed air systems – offered through an online training

LMS Nordic is a small expert company in Sweden, operating only in the compressed air segment. The company started in 2009. LMS Nordic develops courses in compressed air, mainly through on-line training at different levels. From starter courses that give all personnel who encounter compressed air a good insight into how compressed air is produced, why compressed air is expensive, important safety aspects and compressed air's climate impact. The courses create immediate results in the form of lower compressed air consumption and lower pressure.

The compressed air online training offers the possibility to take the course online 24/7/365 when it fits the schedule of the person taking the course. The education starts with preparations where the participant gets information material before the realisation of the course. The course itself takes 45-60 minutes. After the course, the participant applies the new insights on their own compressed air system, and report back identified measures and possible safety issues. The course management then encourages the participants to implement at least one improvement a week until the list of suggested improvements has been cleared. By positive and supportive feedback, the participant is encouraged to work with continuous improvements, which result in quick return on investment.

The energy saving potential in compressed air systems is estimated to be in the following areas[1]:

Leakages	42 %
Optimisation	26 %
Motor checkup	10 %
System design	12 %
Reuse	10 %

All the measures above are treated in the online course.

The training aims to change behaviours and old habits. In a follow up, 84 % of the participants have reported that they will be more restrained in the use of compressed air. About 42 of the participants reported back that they could lower their operating pressure. For a 7-bar system, a 1 bar pressure reduction lowers the flow by 15 % and decreases energy use by 8 %.
Over 80 % of participants have found leakages, and 30 % of these were repaired immediately.

In addition to reduced energy use, participants identified safety issues in their work environment which they can fix. Examples include e.g. lack of shut down valves, oil leakage on floors, too loud noise and missing protective gear.

LMS Nordic thinks that all end users using compressed air should be forced to have a responsible person, that have adequate education in compressed air operation and economy. Since there is very little knowledge about Key Performance Indicators (KPIs) for compressed air, most industries have very little knowledge about how efficient their compressed air systems are.

By continuous monitoring, KPIs could be compared among similar end users, and sensors could also warn if the consumption per sector or zone passes certain values. Digitalisation could also organise systematic maintenance.

Through the CALMS compressed air management platform, businesses can connect their compressed air systems to a platform for continuous monitoring and analysis[2]. Artificial

[1] CAS Europe, https://www.compressed-air-systems.com/
[2] https://calms.com/

Intelligence-based algorithms can monitor numerous parameters and optimise operation and warn when KPI's are deteriorating.

More information: www.tryckluftsutbildning.se/

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