Deep breaths

Optimizing airflow for underground mines

MICHAEL LUNDH, JAN NYQVIST, MATS MOLANDER – From August to October 2010, the world held its breath. Trapped 700 m below the surface of the Atacama desert in Chile were 33 miners. Their entrapment focused minds on the fragile essentials of life: environmental temperature, food, water and air. As commodity prices rise, previously “inaccessible” resources become economically viable. But worthwhile market prices and investment thresholds alone do not overcome the physical and technical challenges that harvesting these remote resources present. Physical limitations remain, which define what can be reasonably and, more importantly, safely reached. But new technologies continue to appear and evolve, allowing humans to continually redefine these limitations. New frontiers are reached, but this is only possible by ensuring that the support systems for life keep pace.

Ventilation consumes a significant amount of energy, typically 100 GWh/year which can be as a much as 50 percent of the total energy consumption for underground activities.

1 A ventilation duct in an underground mine

Underground mines today often operate at depths of down to 2.500 m with some gold mines, even down to 3.600 m. That's as far below the surface of the earth as La Paz, in Bolivia, is above it. The trend is that mining in the future will be mainly underground and at even deeper levels, in remote locations. The mining industry, characterized today by a high degree of mechanized mobile tasks in a harsh environment, is actively seeking automated solutions to meet the future demands of safe, sustainable and productive operations.

Underground air is polluted by hazardous gases such as CO, NO_x, and CO_2 from diesel-driven equipment and blasting, and also radon and methane (in coal mines) can be found naturally in the ground. Proper ventilation is needed to assure a healthy working environment in an underground mine → 1. The purpose is to distribute fresh air to the production areas where mine personnel are located. It is a support function that interacts highly with production. Ventilation consumes a significant amount of energy, typically 100 GWh/year which can be as a much as 50 percent of the total energy consumption for underground activities.

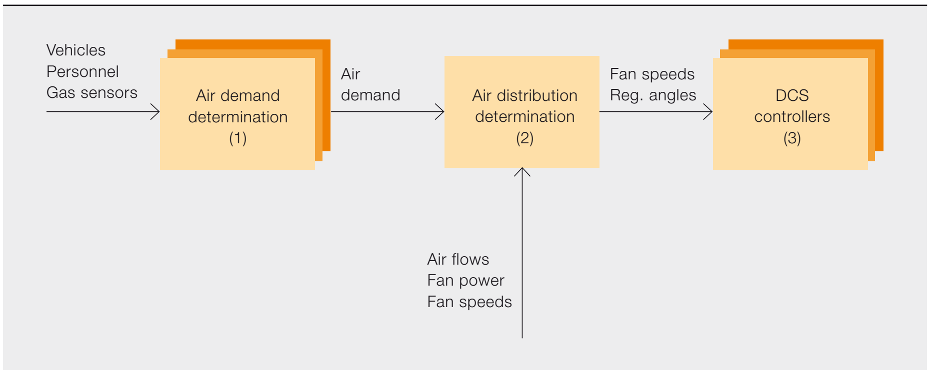
Fresh air must be distributed to the production areas where mine personnel are located and the incoming air might need to be heated or cooled.

Today, main fans on the surface feed the mine with fresh air, which is distributed underground where needed by fans and/or air regulators. The incoming air might need to be heated or cooled. The state-of-the-art technology for control is ventilation on demand (VoD); however, many mines are not controlled at all. But even VoD has drawbacks: There is no feedback control and VoD uses a complex or weak fan/air regulator relation model.

ABB now offers a new unique method for mine-wide coordinated control of the fans and the air regulators, to achieve an energy-optimized and reliable solution that automatically feeds the mine with

Title picture
One third of the world's mined copper comes from the driest desert on earth, the Atacama desert in Chile. Photo courtesy: © 2013 Michael Vogel.

2 Overview of mine ventilation control function



the required air. The solution is based on empirical models and relies on feedback from air sensors, which can be, for example, gas, flow or temperature sensors. Multivariable models describe how changes in the speed of fans affect both the airflow and the pressure over fans. The parameters in the models are obtained empirically from operational data which makes the model easily adaptable for new conditions.

Applying MPC

Advanced process control has been applied successfully in many areas, eg, in chemical processes and in refining.

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The most widespread approach is model predictive control (MPC) [1], the origins of which can be traced back to the 1970s.

A model predictive controller utilizes an explicit model to predict the future response of a plant. Based on this it is possible to determine control signals that affect the plant so that the desired response of the plant is obtained. Since the desired behavior is often a trade-off between conflicting goals, an optimization problem is formulated to find the "best" solution. A dynamic model that describes the plant is essential. Accomplishing a dynamical model can be time consuming: In normal process-industry advanced process control (APC) projects, the biggest effort is spent on finding a sufficiently good model. Normally the modeling consists of a plant testing phase where the inputs are agitated to excite the plant outputs. Both inputs and outputs are logged and these logged signals are then used by mathematical methods to determine a model. This is referred to as system identification [2].

The new approach for mine ventilation is inspired by the MPC methodology. The underground mine challenges the MPC technology because the mine is continuously changing. New tunnels are opened for production and out mined tunnels are closed. New fans and ventilation ducts will be added when the mine is developing. There can also be unplanned changes of the structure, eg, after blasting. Through automated system identification based on operational data or triggered experiments the simple dynamic relation model can easily be adjusted for the new conditions.

Overview

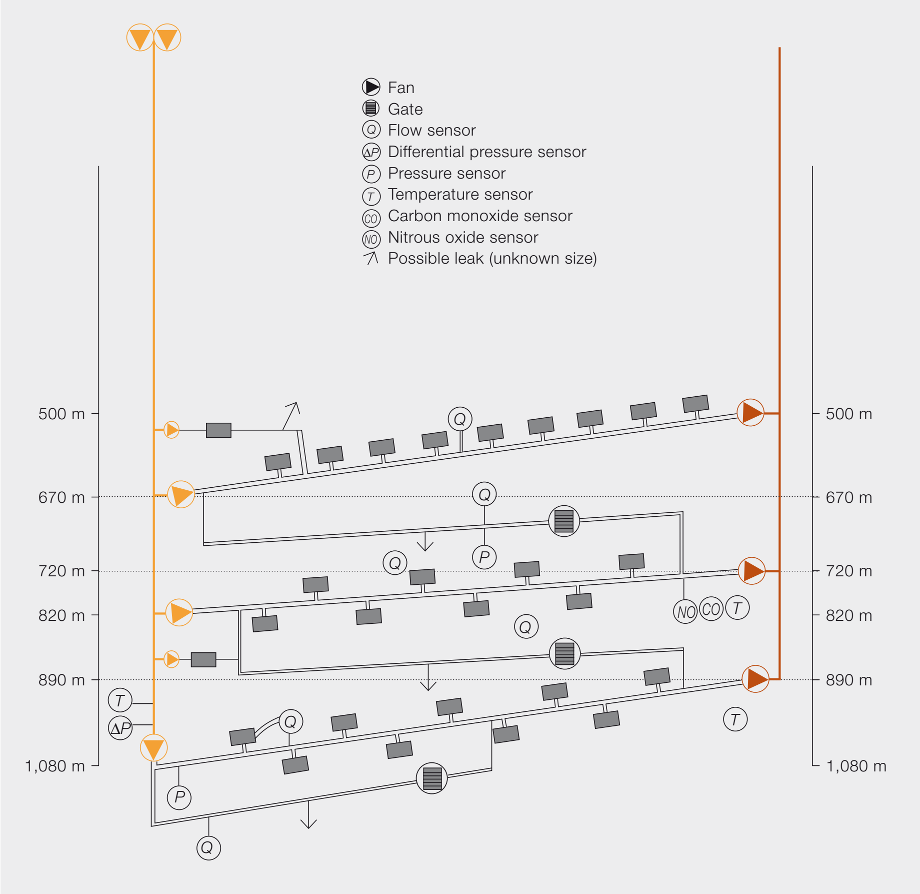
The new approach for mine ventilation has similarities to the VoD currently in use. The structure can be divided into three levels for both types of solution. ➔ 2 shows an overview of the function.

1) The top level determines the actual air demand in various airways in the mine. The demand is obtained from the presence of vehicles and persons in particular locations. Demand may also be determined from sensors, measuring concentrations of different gases in the mine. There may also be some airways where it is of interest to keep the flow as

Through automated system identification, based on operational data or triggered experiments, the simple dynamic relation model can easily be adjusted for the new conditions.

The optimized fan speed is determined from the air demand in various airways, properties of the fans and motors driving the fans.

3 A schematic sketch of the mine used for testing



low as possible, eg, to control access ramp flows.

2) The second-level functionality determines the distribution of air by optimizing the speed of fans that drive the air through the mine. The optimized fan speed is determined from the air demand in various airways, properties of the fans and motors driving the fans. The second level may also include the opening angles of the air regulators that are used to control the air flow. The fan speeds and the air regulator angles are determined in order to minimize the actual total power used for ventilation while still satisfying the air demand. This minimization is based on a model that relates changes in fan speeds to changes in air flow and actual used power.

3) The optimal fan speeds and air regulator angles are then used as set-points for lower-level controllers in the distributed control system (DCS).

In the new MPC solution, overall air distribution optimization is carried out on the second level.

Modeling

The air distribution in the mine is affected by fan speeds and, if present, opening angles for dampers. These are the actuators in this control system. There is interaction between actuators and airflows in the mine. This means, for example, that a changed speed for a fan will not only affect the airflow in the airway where the fan is located, but also affect airflows in other airways. This interaction is what makes it difficult to control the airflows in

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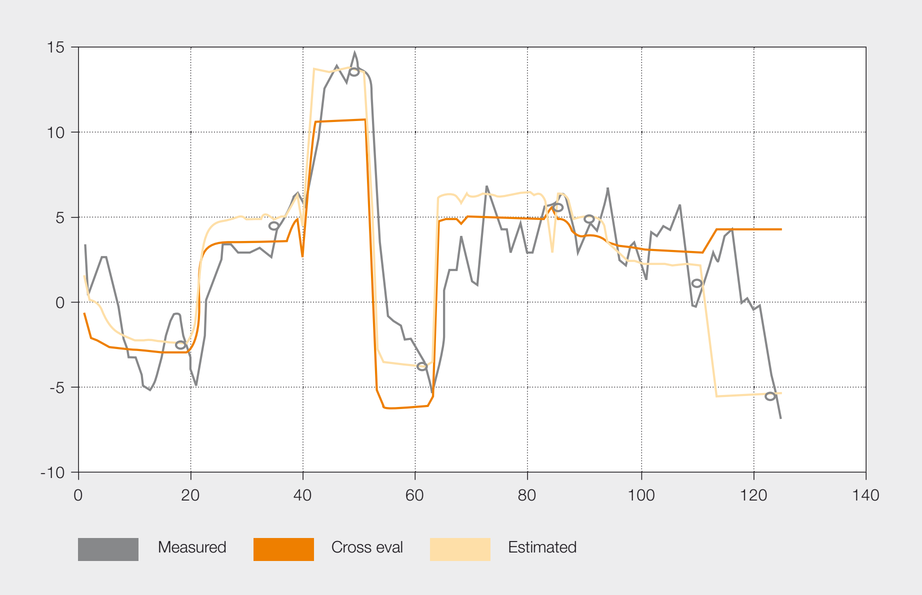

an optimal way. It is therefore important that the model captures this behavior of the mine.

Dynamic multivariable models could be used to describe the mine. Such models are used in many applications, eg, in the refining industry. A drawback with these models is that substantial effort is required to obtain a model. This is undesired here since the shape of the mine is consistently changing, through extensions, and accidental new paths for air flow may occur due to blasting. It is not practical or useful to spend weeks building a new accurate dynamical model of the mine each time a change occurrs.

In this case a simple static multivariable model, which is able to capture the essential interaction and impact from changes in the actuators, is used. The model is described on the incremental form

$$\Delta Q = H_q \Delta\beta$$
$$\Delta p = H_p \Delta\beta$$
$$\Delta E = H_e \Delta(\beta^3)$$

where Q is a vector of measured air-flows, p is a vector of pressures over fans, β is a vector of fan speeds and E a vector of fan powers. Δ indicates changes between two samples. The coefficients in the matrices H_q, H_p, and H_e are obtained from simple experiments, or from normal operational data that enables the automation of system identification.

The objective for the control is to maintain the desired airflow in various airways, while the power required to run the fans is minimized.

Measurements

To identify the model of the mine ventilation system and to be able to use it for control, a number of variables must be measured:

- Gas concentration and/or air flows in various locations to be controlled
- Fan power of the fans to be controlled
- Fan speed of the fans to be controlled
- Pressures over fans

The controller adjusts the actual fan speed based on current demand.

Control

The objective for the control is to maintain the desired airflow in various airways, while the power required to run the fans is minimized. Airways that feed production areas with air must have an airflow that exceeds a required flow. Other airways may be requested to have airflows which should be kept as small as possible.

This can be formulated as an optimization problem where new fan speeds are determined to minimize the actual fan power.

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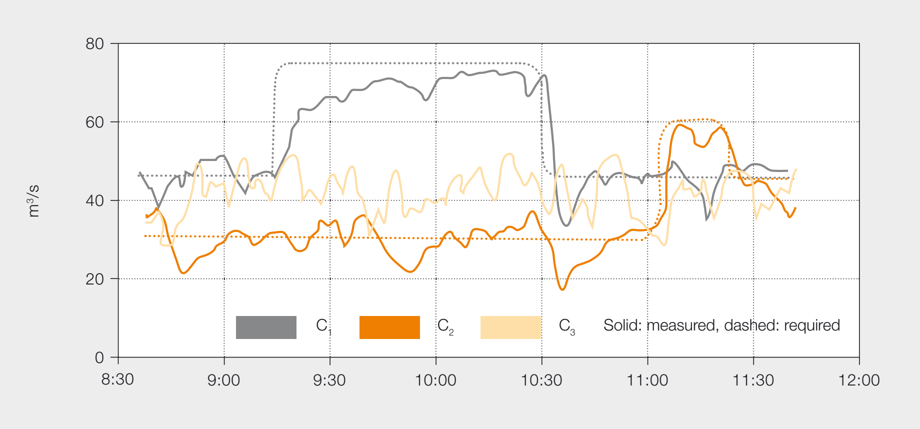
5 System adjusting the airflow to a step change of demand



During minimization, constraints on airflow and on differential pressures are taken into consideration:

$$Q_{lo} \leq Q(k) \leq Q_{hi}$$
$$\Delta p_{lo} \leq \Delta p(k) \leq \Delta p_{hi}$$

In addition, there are limitations on the fan speeds:

$$\beta_{lo} \leq \beta(k) \leq \beta_{hi}$$

This optimization problem is solved on a cyclic basis where new fan speeds are calculated. The initial values for each optimization are provided by filtered values of the measured signals.

Field tests

The new method of controlling the mine ventilation in an optimized way has been tested in an operating underground mine. The mine was already equipped with an ABB VoD system connecting all the fans and sensors.

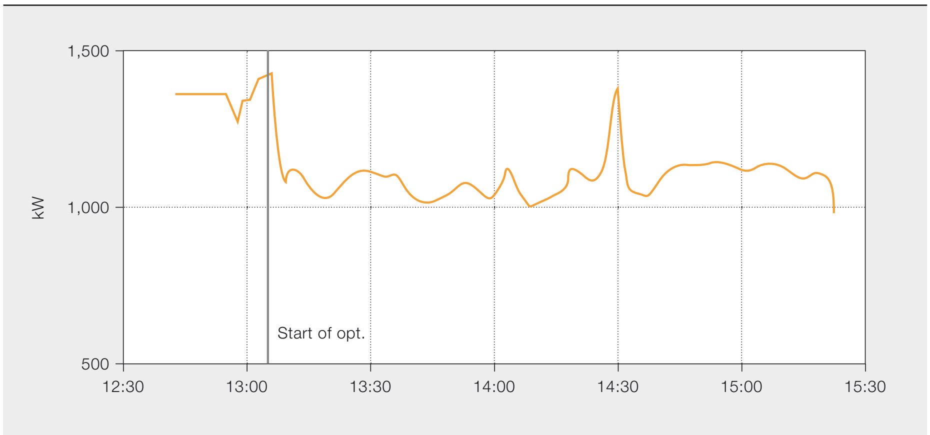
Despite the evolving nature of the mine there is no break in the efficiencies from which the mine benefits.

A schematic sketch of the mine is shown in → 3. The controlled area of the mine consists of three production levels from a depth of 500 m down to 1.080 m. There are two surface fans at the air intake, plus one fan at the inlet and one at the outlet on each production level. The orange line represents incoming fresh air and the brown line outgoing polluted air. In each level, and in the access tunnels between the levels, air speed is measured with ultrasonic flow sensors. The locations of the sensors are marked with a Q in the sketch. For each fan the static pressure rise is also measured.

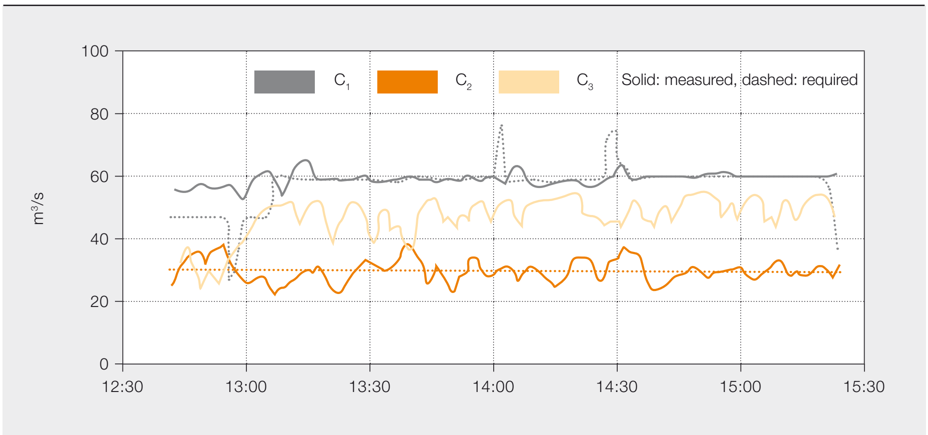
Vehicles are entering and leaving production areas all the time, meaning the air demand for the airways to these production areas changes, and the current VoD system for ventilation will change the fan speeds accordingly. This will provide the necessary excitation to identify the model. After appropriate filtering and the removal of high-frequency variations, the static models of the mine, described above, are identified by the simple least-squares fitting method. An evaluation of two such models is shown in → 4. One of the models was identified using the same data as the measured data plotted in the figure (Estimated) and the other (Cross eval) was identified using a completely different set of data.

The fan optimizer, based on the identified models, was tested over two days where the ventilation of production levels was controlled by the optimizer. The result, as recorded by ABB's System 800xA during the test, is shown in → 5. The chart shows how the system adjusts the air flow, in the first level of the three level mine, to a step change of demand (solid grey line) and the air flow in the second level to a demand step change (solid dark orange line).

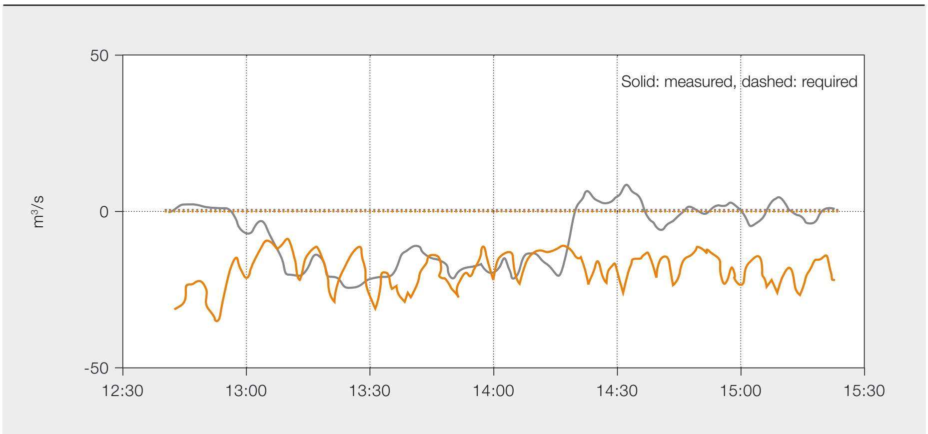
6 Operation plot of the model showing reduced fan power



6a Total fan power



6b Cell flows



6c Access ramp flows

A plot of another registration recorded during the operation is shown in → 6. The plots show how the optimizer can substantially reduce the fan power while fulfilling the air flow demands in the airways. The tests have shown a possible reduction of fan power of 30 to 50 percent compared with the existing system in operation, while maintaining the same airflows.

Air achievements

The field tests indicate that applying the simple empirical models on an underground ventilation system one can achieve:

- Automatic control of a healthy working environment in an underground mine adjusted to current air quality demand
- Automatic adjustment to new working conditions when the mine is developing
- Significant fan power reduction by optimizing distributed loads on existing fans
- Robust and reliable automated ventilation through feedback control

The working environment benefits from receiving optimized air flows that best fit the activity in that location.

Applying these dynamic empirical models to mine ventilation systems brings multiple benefits. Not only does the mine owner or operator benefit from reduced running costs, but the working environment benefits from receiving optimized air flows that best fit the activity in that location. Despite the evolving nature of the mine, the existing model keeps pace, ensuring that air and fan optimization is continuous. That also means there is no break in the efficiencies from which the mine benefits, even in some of the harshest and most remote working environments.

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