IoT-based Mine Ventilation Control System Architecture with Digital Twin

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Abstract. **This paper considers a dynamic ventilation system of the underground mining. The research is relevant from the point of view of safety and energy saving of mining operations, since the process of ventilation of underground mining companies consumes from 30 to 50% of all company electricity. Existing methods of ventilation control often do not ensure rational energy consumption, as they do not take into account the dynamics of air distribution and changes in environmental parameters. The proposed method includes basic algorithms for calculating the interrelationship of physical parameters of general natural draught between the trunks. The method includes: calculation of the draught's power; calculation of productivity and the choice of the required mode of operation for the main fan unit (MFU) considering the inertia of the ventilation system; dynamic calculation of the control signal on the fan unit taking into account the impact of the general natural draught. The method is focused on the implementation of the TICK stack used to create IoT applications as part of the Cyber-Physical System (CPS) for ventilation based on the InfluxData platform. The proposed CPS architecture consists of four subsystems: physical object subsystem, IoT network and computing infrastructure - ICT infrastructure, digital twin, user interface. CPS architecture provides processing of data from energy meters, controllers and air environment parameters, implemented in on-line and off-line calculation units.**

Keywords **-- Cyber-Physical System, Information System Architecture, Internet of Things, Digital Twin, InfluxData Platform, Modelica.**

I. Introduction

Most large mine enterprises, factories and other mine production facilities are equipped with powerful air ventilation equipment. The process of ventilation of underground mining companies consumes from 30 to 50% of all electricity consumed by the company, this is thousands of gigawatts per year, [1-3]. The ventilation is influenced by many random factors, such as changes in the parameters of the outside air, the movement of vehicles in the mine workings, etc. In winter, the air is heated in the mine heater systems before it is fed into the shaft. Inefficient use of energy for air is caused by the lack of methods and mechanisms to control air distribution in underground mines, as well as devices and systems that allow the supply of air to the required volume to the working areas and block the way for its entry into the worked-out space.

In addition to the energy consumption of the main fan unit (HVU), the volume flow rate required for the safety of the underground mining operation is several times higher than the volume flow rate required for the HVU, which is a problem in air treatment, and which is required by the Safety Rules. Because air is inherently a thermal insulator, it requires a significant amount of energy to heat and cool it.

The methods of air treatment and ventilation control nowadays consist in maintenance of the ventilation set by the operator (usually strongly overestimated) volume flow rate. Regulation and optimization of the system's energy efficiency are not performed in both normal ventilation and air treatment modes. Existing knowledge shows that such dynamic control tasks could be solved by using cyber-physical (CPS) system with sensor and actuator components interacted by available network protocols based on the Internet of Things (IoT) [4-8, 10].

The main technological leaders who received key scientific and practical results within the framework of energy efficiency systems using the CPS: Schneider Electric, Honeywell, Siemens, Philips, Huawei, General Electric, ABB, IBM and others. Computerized control methods in the CPS of industrial enterprises are being actively studied.

The basic principles of building a hardware-software complex for intellectual control of engineering equipment IoT are considered in the works of J.E. Seem, L.C. Braga, Zhou Honbo, Chaouchi Hakima, Weber Rolf H., Hong T., Feng W., Lu A., Xia J., Yang L., Shen Q., Im P., Bhandari M., Jianchao Zhang, Boon-Chong Seet, Tek Tjing Lie, Wonga J.K.W., Li H., Wang S.W. The results of using IoT equipment and open protocols of data transfer, allocation of control levels, application of distributed database and cloud services that allow remote control are obtained.

Thus, for the efficient and safe operation of the ventilation system in optimal mode, the process control system in underground mining operations must be considered as a CPS, which implements wireless data transmission underground, their processing and analysis, as well as the issuance of control signals to the actuators, taking into account the predicted air distribution between the mines.

In such case the effective functioning of the air supply systems in a mine enterprise can be supported only through the improvement of ventilation method via industrial IoT applications. The present task can be solved by developing and researching ventilation digital twin, which can be "built-in" into existing SCADA systems.

II. Method of natural draught calculation between shafts for digital twin implementation

To simplify the calculations, the following assumptions are accepted:

1. air density depends on its temperature and pressure, which can be measured using sensors, a number of coefficients are also used for its calculation [9, 10];

2. air temperature in the near-barrel courtyard of the ventilation shaft depends on the depth of the mine and practically does not change over time;

3. the mouths of the mine shafts are at the same high altitude;

4. the number of shaft shafts in underground mining enterprises can be different, therefore, the value of the volumetric air flow rate for ventilation of the mine (mine) is determined at the stage of calculating the required ventilation mode. This value is controlled with the help of air flow sensors, which are necessarily present in the ventilation shaft and in the channels of the HVU;

5. the value of the aerodynamic drag of the mine changes over a long period of time, therefore, to determine its value by measurement, you can select the interval, for example, once a year. If its exact value is required, then you can use the methodology for calculating the aerodynamic drag of a mine described in [11-13];

6. Do not take into account surface air leaks arising from the operation of the HVU.

Natural draught operates between reported workings, in particular between shafts. The formula used to calculate the natural draught between the two intercommunicating trunks is the same as the one used to calculate the natural draught:

$$h_{e,i} = (\rho_1 - \rho_2)\cdot g \cdot H_{ais}$$

where $h_{e,i}$ - natural draught between the i-th pair of trunks, Pa; ρ_1, ρ_2 - average air densities in 1 and 2 intercommunicating trunks, kg/m^3, respectively; g - acceleration of free fall, m^3/s; H_{ais} - height of intercommunicating trunks, m.

Natural traction acts between communicating workings in particular between mine shafts (fig. 1) and can be calculated according to algorithm 1.

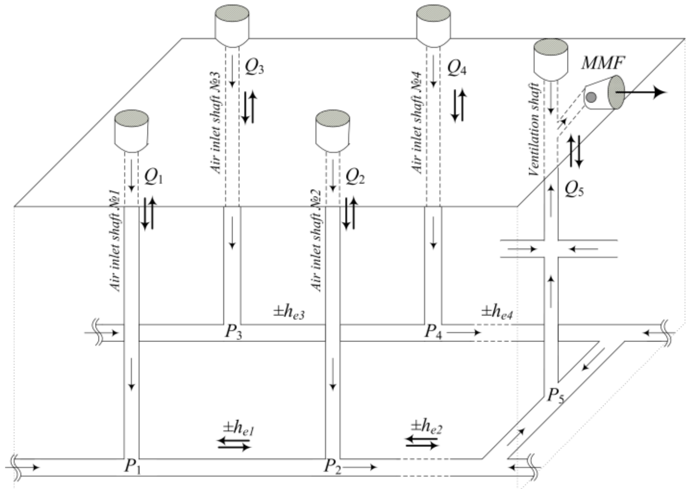

Fig. 1. Simplified schema for air distribution between shafts

Algorithm 1. Calculation of natural draught between shafts

Procedure $h_{e,i}$ (H_{ais}, $S1$, $S2$, K, ΔPi, Q_i, R_a, t_a)

Step 1. Calculation of the aerodynamic resistance of the air supply shaft R_1

$$R_1 = \alpha_1 (K\cdot H_{ais}/S1^{2.5})$$
$$\alpha_1 = 0{,}096138$$

Step 2. Calculation of aerodynamic resistance of the ventilation shaft R_2

$$R_2 = \alpha_1 (K\cdot H_{ais}/S2^{2.5})$$
$$\alpha_1 = 0{,}096138$$

Step 3. Calculation of the aerodynamic resistance of the underground part of the mine

$$R_i = \frac{\Delta P_i \cdot N}{9{,}81 \cdot Q_i^2}$$

Step 4. Air density calculation for the air supply shaft ρ_1

$$\rho_1 = \frac{\alpha_1\left[P_a(\alpha_2 + 2t_a - K_p H_{ais})\right] - \alpha_4 R_1 Q^2 (\tau + t_a)}{(\tau + t_a)\left[\tau + t_a + H_{ais}(K_p - \alpha_3)\right]}$$

$\alpha_1 = 0.2325$; $\alpha_2 = 546.3$; $\alpha_3 = 0.01705$; $\alpha_4 = 0.0075$; $\tau = 273.15$; $K_p = 0{,}00767$ °C/m

Step 5. Air density calculation for ventilation shaft ρ_2

$$A_1 = \frac{\alpha_1(\tau + t_c - H_{ais}(\alpha_3 - K_v))}{\tau + t_c - K_v H_{ais}}$$

α_1=0.2325; α_3=0.01705; τ=273.15; K_v=0,00923 °C/m; t_a - air temperature in the ventilation shaft near-barreled yard, °C (depends on the depth of the mine and practically does not change over time

$$A_2 = \frac{P_a + \alpha_3 \rho_1 H_{ais} - \alpha_4 (R_1 + R_2) Q^2}{\tau + t_c}$$

$\alpha_3 = 0.0735$; $\alpha_4 = 0.0075$; $\tau = 273.15$

$$A_3 = \frac{P_a + \alpha_3 \rho_1 H_{ais} - \alpha_4 (R_1 + R_2 + R_3) Q^2}{\tau + t_c - K_B H_{ais}}$$

$\alpha_3 = 0.0735$; $\alpha_4 = 0.0075$; $\tau = 273.15$

$\rho_2 = A_1[A_2 + A_3]$

Step 6. Calculation of the natural thrust of $h_{e,i}$

$h_{e,i} = (\rho 1 - \rho 2)\ gH_{ais}$

$g = 9.81\ m/s^2$

return $h_{e,i.}$

III. Method of the commonplace natural traction calculation

The work of the HVU is influenced by the commonplace natural traction. It has been established in [8] that the value of the natural traction is defined as the sum of the natural traction between each pair of trunks, algorithm 2. Thermal depression is written as *T* and determined by the difference in values between ρ_1 and $\rho_{2;}$ *n* is the number of pairs of mine shafts communicating. Here it is necessary to determine the value of all natural rods between the trunks and find their sum.

Algorithm 2. Calculation of the commonplace natural traction

Procedure h_e
  $h_e = 0$
  for $i = 1, 2, ..., n$ **do**
    if $T > 0$ **then**
      $h_e = h_e + h_{e,i}$
    else
      $h_e = h_e - h_{e,i}$
return h_e

Method of the performance calculation and selection the desired HVU mode of operation

The pressure developed by the HVU can be calculated by the formula [4, 6]:

$$h_{HVU} = A + B \cdot Q_{HVU} + C \cdot Q_{HVU}^2$$

Here Q_{HVU} - HVU capacity, m^3/sec; *A, B, C* - coefficients describing the aerodynamic characteristics of the discharge fan (are in the calculation of the characteristic curve by the least squares method) [4, 6].

Working in conjunction with the common natural draught, the HVU will create pressure and develop airflow according to the dependence:

$$h_{HVU} + h_e = R \cdot Q_{HVU}^2 ,$$

Then,

$$A + B \cdot Q_{HVU} + C \cdot Q_{HVU}^2 + h_e = R \cdot Q_{HVU}^2 .$$

Having designated $A_1 = C - R_{rud}$; $C_1 = (A+S_e)$; $a = B/A_1$; $b = C_1/A_1$ we determine the performance of the HVU, taking into account the action of general natural traction:

$$Q_{HVU} = -\frac{a}{2} + \sqrt{\left(\frac{a}{2}\right)^2 - b} .$$

If the draught acts against the direction of air flow generated by the MFU, it is necessary to increase its efficiency, but if the commonplace natural draught is directed according to the required direction of air flow, i.e. promotes ventilation, it is possible to reduce the performance of the fan, thereby reducing the energy costs for ventilation.

The Q_{HVU} value in all formulas is also a value without surface air leakage.

Ventilation CPS architecture based on the InfluxData

The InfluxData platform is an information aggregator, designed to create various applications and services based on IoT technologies by connecting multiple data collection interfaces, protocols, supporting time series databases and third-party visualization software.

It can be integrated as an add-on for the existing SCADA system to implement a large number of analytical functions that contribute to improving the efficiency and quality of assessing the energy efficiency of ventilation. Since the platform is not specialized for use in the mine CPS applications for monitoring and controlling industrial equipment (ventilator and heater, in particular) it requires adaptation of the calculation units and the creation of a unique digital twin, fig. 2.

The InfluxData platform based on TICK stack that offers to develop various IoT applications using tools: T - Telegram, I - InfluxDB, C - Chronograf, K - Kapacitor. The combination of TICK tools forms InfluxData platform as an information aggregator, which can be complemented by applications and services through open interfaces and protocols connections.

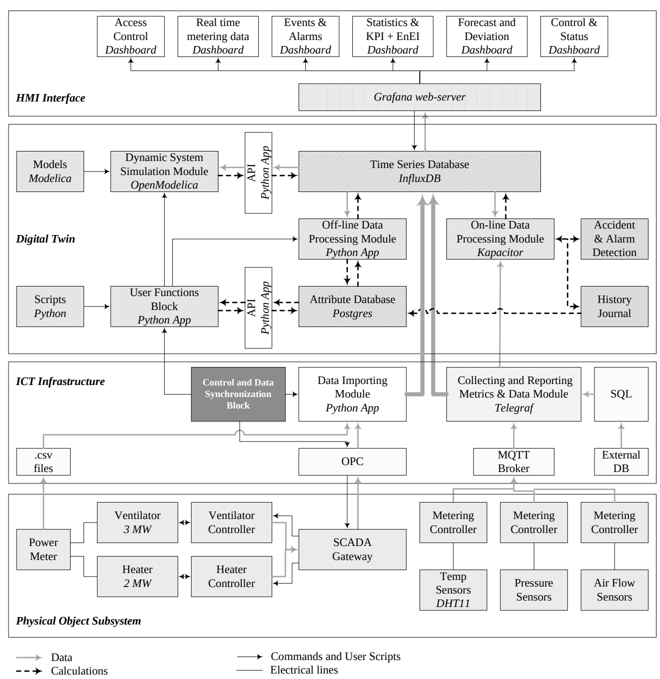

Fig. 2. Simplified monitoring and control of ventilation equipment CPS architecture with Digital Twin subsystem

CPS consists of four subsystems: physical object system, network and computing infrastructure, digital twin and human-machine interface. The basic principle of building the target system is the concept of cyber-physical control, which is built network-centrically with the central link of data accumulation, analysis and management [14, 15]. The central link interacts with the intelligent nodes of operational control based on SCADA or intelligent nodes of cyclic control using OPC interface or Modbus RTU.

The implementation of the above algorithms 1-3 in the system of ventilation of underground mining enterprises in many ways intersects with the task of maintaining an unbalanced configuration of the temperature field in the system of communicating with each other premises (chambers) with minimal energy consumption [16, 17]. For construction of such thermal models, as well as for modeling of control system, MatLab package is often used [18, 19], which in conditions of high interoperability of CPS components is more expedient to replace with OpenModelica package.

Transition to open communication interfaces, protocols of the Internet of things, for example MQTT, and the central link realising cloud computing, promotes reduction of expenses for designing, modelling, introduction and operation of technical objects [8, 20]. In this case for the solution of energy saving problems the mechanisms of predictive analytics can be used [21], with the implementation on popular Python libraries Keras, TensorFlow and Padasip. The accurate prediction of changes in parameters can be used for continuous regulation of the technological parameter by the classical algorithm of regulation by feedback in addition to the target function of energy consumption [22, 23].

The control signals for the HVU executive controllers can be generated using the program control unit, also taking into account operator commands, as shown in [24]. It is reasonable to implement the definition of transient functions of the corresponding channels of the control object when identifying the reaction of temperature parameters in the mine (mine) at the step influence on the channel, [25 - 27], using historical data in the InfluxDB database and event log in Postgres.

As a computer experiment, the task of online forecasting of energy consumption 24 hours ahead for the ventilation system using input data from the simulation model in Modelica programs was solved. In the course of the solution a trainable predictive model of energy consumption was obtained (Fig. 3), which combines the classical models by adapting their weights with a multilayer perception in Python (Keras library). Few simple short term load forecasting models are used like naive model CLD – copy last day, HW – Holt Winters model, Ndays – average calculations in N=10 days, AR&RLS – linear autoregression model, Feature Extraction – linear regression model with time and value features from model. The key point of this experiment is the possibility to take into the Python script different values from Modelica model, that increase the quality of the prediction. The accuracy was calculated via RMSE metric.

Using the algorithm proposed in the work of the calculation of the house-wide natural traction, taking into account the changing and predictable its values by analogy with the proposed experimental methodology, you can control the work of the HLU in energy-saving mode.

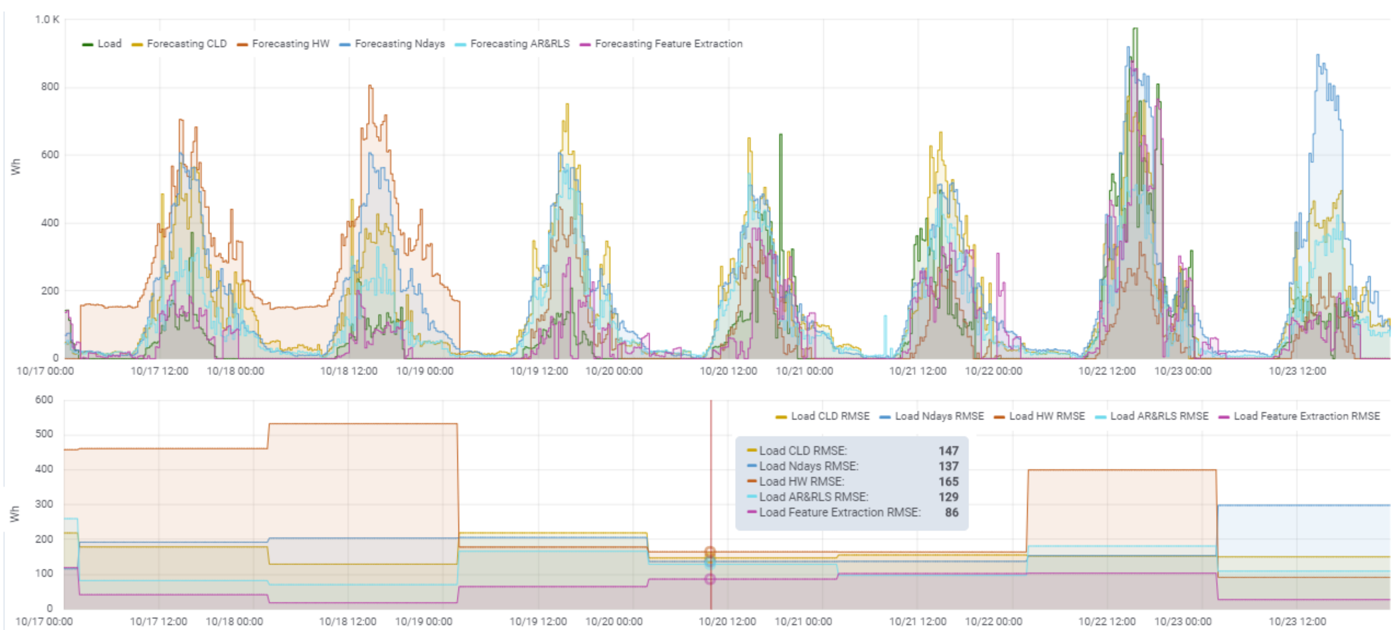

Fig. 3. Visualization of the results of online energy forecasting at the level of digital twin CPS in a bundle Modelica -> Python -> InfluxDB -> Grafana

Conclusion

Accumulated in InfluxDB information about the object for the entire period of operation is used to refine the calculation of daily natural draught and HLU productivity in OpenModelica by using in the model exogenous data on the forecast of changes in the parameters of mine (mine) operation and the parameters of outdoor air, which is implemented in Python. Thus, the platform of the presented architecture will allow to provide predictive control, on predicted parameters acting on object, and to compensate them in conditions of inertia of process of ventilation. Constant adaptation of control command calculations to reality and forecast will allow to continuously optimize the settings of the algorithm of regulation of air supply of underground workings, guaranteeing energy efficient operation of local fan control circuits.

Thus, for efficient and safe operation of the ventilation system in the optimal mode, the process control system at underground mining enterprises can be considered as a CPS, which implements data transfer from the SCADA level to the level of the platform Internet of Things, their processing and analysis using predictive analytics, as well as the issuance of control signals to the actuators, taking into account the simulation of dynamic processes of air distribution between the mine workings.

The study was performed in the framework of the priority direction of the development of science of the Perm branch of HSE "Research of control methods in cyber-physical systems".

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