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INCREASING ENERGY EFFICIENCY OF MINE VENTILATION SYSTEMS VIA MULTIPURPOSE CONTROL OF A MAIN FAN ADJUSTABLE SPEED ELECTRIC DRIVE

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ABSTRACT: The paper focuses on substantiation of a multipurpose control system for a fan frequency variable drive aimed at providing required amount of fresh air on one hand and diminishing energy losses in the system "mains – electrical drive – main fan – ventilation network" on the other hand.

Introduction

The power required to operate a ventilation system can be 25% to 50% of the total power requirements of the mine which results in a remarkable portion of ventilation energy cost (up to 30%) in overall cost of the production. Annual ventilation energy cost can reach 40% of the ventilation system cost. Under current tendency of deep mining and energy cost escalating, the impact of energy-intensive ventilation system on sustainability of mining enterprises is of great importance. So, identifying and capturing energy saving opportunities is essential for cutting down the cost of mine production and achieving the overall optimum profitability of the mine.

It is common that ventilation fans are controlled manually and operated 24 hours per day at maximum capacity of the current day set point. High level of energy consumption is due to a relatively low operational efficiency of fans, exceeded air-flow in comparison with real-time requirements according to a current stage of mining, energy losses in an electrical drive system which depends on fan modes of operation, energy quality in the mine power distribution system etc. Opportunity exists for a decrease in energy consumption by managing the ventilation system to provide only the air required which depends on fresh air-flow demand after blasting, non production time between shifts, travel time to work place, Diesel machinery "off" or "on", non operating time for maintenance or holiday and so on. Implementation of ventilation on demand (VOD) concept [1] requires usage of a mine control system which focuses on using minimal amounts of energy and resources. The system is expected to implement real-time tracking and monitoring of personnel and diesel equipment location and status, control and optimization of ventilation equipment including all fans and air regulators/vent doors, monitoring of air quality and air quantity, real-time evaluation of mine ventilation network, air mass flow and heat balance.

Central role in optimization of air-flow distribution at different levels of a mine plays a control system of a main fan variable frequency drive (VFD), which is considered as subsystem integrated into overall mining process control system. Without the technology application of using motor speed to control fan output, the VOD design would not be as efficient or have the flexibility as required for a safe and robust system. The paper presents a complex systems approach for development of energy efficient mine ventilation system which is intended to minimize energy losses at cross-sections of energy flow in the system "mine supply grid – electric drive – main mine fan – mine ventilation network" via multipurpose control of main fan adjustable speed drive (Fig1). The paper focuses on speed control of main fan productivity, interaction of electrical drive system and power supply grid, minimization of energy losses in electrical drive system on the basis of a search algorithm and optimal start-up control law applications.

Mechanical, speed and combined control of a main mine fan

Fans are classified into two main categories: centrifugal and axial-flow. Fan selection depends on physical constraints of the site, especially depth of the mine. Analysis of energy consumption and energy savings potentials has been fulfilled on the basis of centrifugal and axial-flow fan performance curves which were approximated as follows

$$H(Q) = a_0 Q^2 + a_1 Q + a_2 \ , \qquad (1)$$
$$P(Q) = b_0 Q^2 + b_1 Q + b_2, \quad \eta = H \cdot Q / P \ ,$$

where H – pressure, Q – air flow, P – shaft power, $P_a = H \cdot Q$ – fluid power, η – fan efficiency, a_k, b_k – polynomial coefficients depending on a variable vane angle α , which for a centrifugal fan varies in the range $\alpha = 0, 10....70^0$.

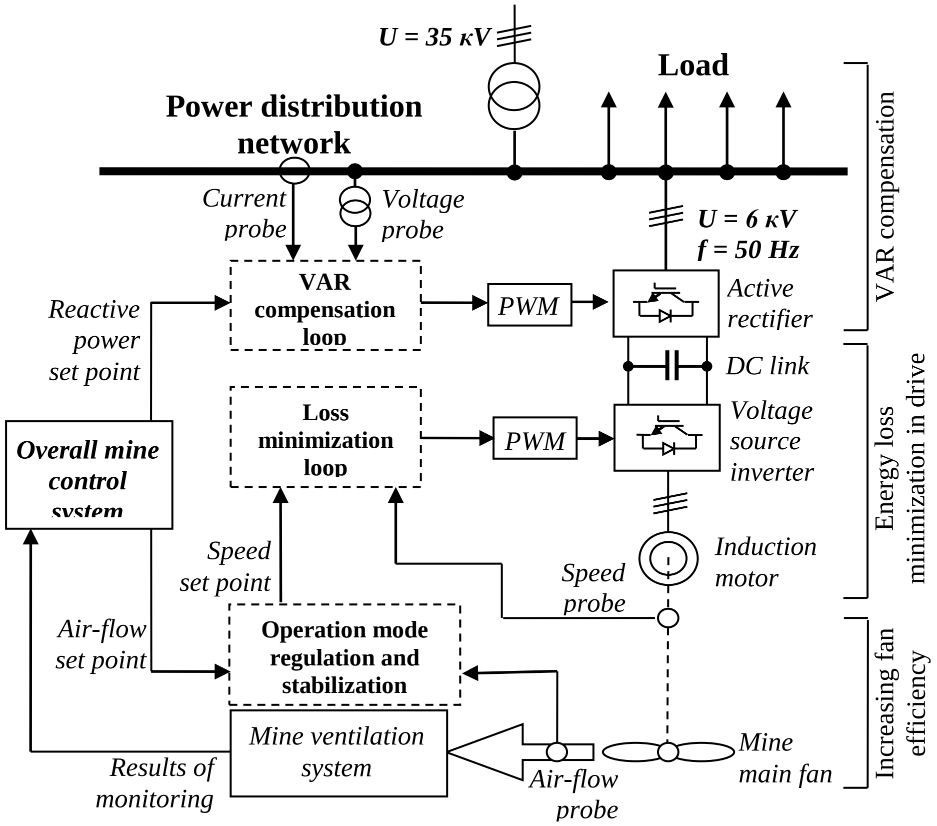


Fig.1. Structure of frequency variable drive and control system of a main mine fan

Using affinity laws

$$Q = Q_0 \cdot \hat{\omega}, \quad H = H_0 \cdot \hat{\omega}^2, \quad P = P_0 \cdot \hat{\omega}^3 \qquad (2)$$

and expressions (1) we can write speed-controlled performance characteristics:

$$H(Q,\hat{\omega}) = a_0 Q^2 + a_1 Q \cdot \hat{\omega} + a_2 \cdot \hat{\omega}^2 , \quad P(Q,\hat{\omega}) = b_0 Q^2 + b_1 Q \cdot \hat{\omega} + b_2 \cdot \hat{\omega}^2 \qquad (3)$$

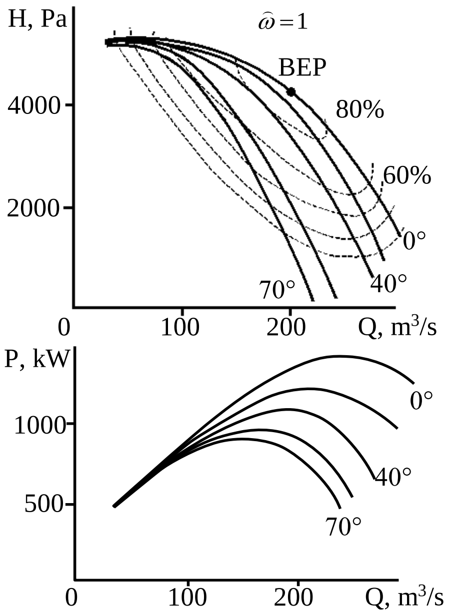


Fig.2. Centrifugal fan curves at a nominal speed ω_0=750 rpm controlled by changing the vane angle α

where $\hat{\omega} = \omega / \omega_0$, ω_0 - nominal speed value, P_0, Q_0, H_0 – rated operation mode characteristics.

For vane angle $\alpha = 0°$ and best efficiency point (BEP) coordinates ($H_0 = 4700\,Pa$, $Q_0 = 200\,m^3/s$, $P_0 = 1.6\,MW$, $\eta_0 = 84\%$) polynomial coefficients a_k, b_k are as follows: $a_0 = -0.08$, $a_1 = 13.3$, $a_2 = 4920$, and $b_0 = -9.42 \cdot 10^{-3}$, $b_1 = 4.64$, $b_2 = 487.5$.

Centrifugal fan performance curves for aero-dynamical and shaft speed control methods are presented in Fig. 2 and Fig.3. Fig.3 also comprises a set of yearly operating points over a 10-year cycle of the fan life.

Operating points are defined as intersections of fan and system curves or from equations $H(Q,\alpha) = R \cdot Q^2$, $\omega = \omega_0 = const$, $\alpha = \mathrm{var}$ for an aero-dynamically controlled fan and $H(Q,\hat{\omega}) = R \cdot Q^2$, $\hat{\omega} = \mathrm{var}$, $\alpha = const$ for a speed-controlled fan, where R – equivalent resistance of the airway. At regulating the fan under constant airway resistance, operating point moves along the system curve $H(Q) = R \cdot Q^2$. If the system resistance fluctuates $R = R_a \pm \Delta R$ and the air-flow should be kept at a constant value $Q = Q_a = Q_{ref}$ (Fig.4) stabilization can be achieved by the shaft speed correction within the range $\omega = \omega_a \pm \Delta\omega$, where speed increment $\Delta\omega$ is found from the equation:

$$a_2 \cdot \Delta\hat{\omega}^2 + \Delta\hat{\omega} \cdot (2 \cdot \omega_a \cdot a_2 + a_1 \cdot Q_a) - \Delta R \cdot Q_a^2 = 0 \qquad (4)$$

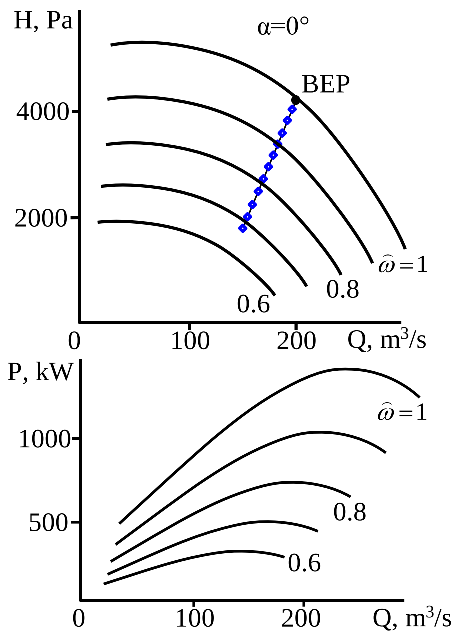


Fig.3. Speed-controlled centrifugal fan at the vane angle α=0° with a set of yearly operating points over 10-year period

A mine can take years to be fully developed. In the beginning of life-time the fan may be substantially oversized and initial operating points may be far from the fan best efficiency point (BEP). Variations of shaft power P and fan efficiency η due to changing of yearly operating points over 10-year fan (see Fig.2) are presented in Fig.5. The graphs have been obtained under conditions that terminal operating points for both control methods coincide with BEP. Analysis of curves obtained indicates that usage of speed control fans gives substantial energy savings due its bigger efficiency as compared to vane angle-controlled fans. Total energy savings over 10-year operational cycle amount to 18·106 kWh.

Figure 6a demonstrates lines of constant efficiency η at decreasing the reduced speed values from the original fan speed. The lines are the parametric representation of function $H(Q)$ where $H = H_{\eta,\alpha} \cdot \hat{\omega}^2$, $Q = Q_{\eta,\alpha} \cdot \hat{\omega}$ and $\hat{\omega} = \text{var}$. Analyzing the graphs we can state that maximum effect of speed control application can be achieved if yearly operating points lies in zone "A" where $0.8 \le \eta \le 0.84$.

For an axial-flow fan, BEP is located approximately in the centre of performance characteristic curves $H(Q,\alpha)$, $\alpha = \text{var} = 30, 35, ...65^0$. In this case, application of both aero-dynamical and speed control methods may provide better efficiency than application of only speed control. Fig 6b represents a set of axial fan curves used for an assessment of possible effect from combined control applications. Yearly operating points are plotted together with constant efficiency zones and performance characteristics obtained at different pitches angles $\alpha = 30, 35...65$.

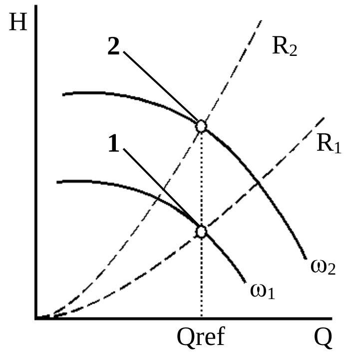


Fig.4. Speed-based air-flow stabilization under variations of the system resistance ΔR=R1-R2

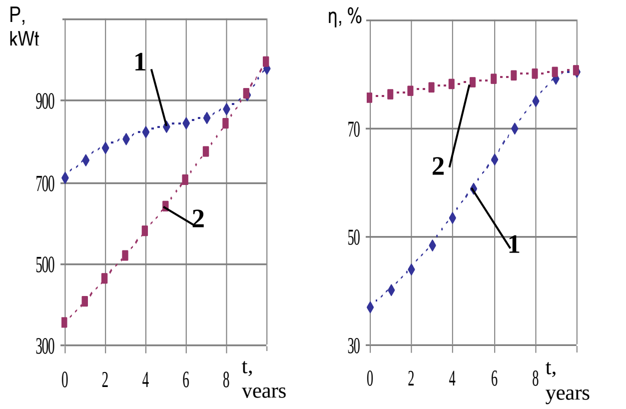


Fig.5. Influence of control methods applied (1 – aero-dynamical, 2 – speed) on shaft power and efficiency of a centrifugal fan during the fan life-time under condition that terminal operating points in both cases coincide with BEP

Results of programmed calculations are summarized in Table1. The data obtained refer to cases of speed control with constant pitch angle $\alpha = 50°$ and combined control based on both angle and speed variations in the range $50° \le \alpha \le 65°$ and $0.44 \le \hat{\omega} \le 1$. As it is seen from Table 1, the combined method gives the most noticeable advantage of 9.2% at the initial operating point.

Fig.7 illustrates displacement of fan curves in relation to operating point 5 (see table1) by changing both pitch angle and shaft speed. In case of speed control ($\hat{\omega} = 0.8, \alpha = 50^0$, Fig.7a) fan efficiency is of $\eta_1 = 77\%$. In case of combined control, efficiency has been increased up to $\eta_2 = 80\%$ by changing both shaft speed $\hat{\omega} = 0.64$ and pitch angle $\alpha = 60^0$ (Fig 7b).

Results of analysis obtained allow us to state that fan correct selection and its proper sizing along with application of the fan optimum control can lead to significant energy savings.

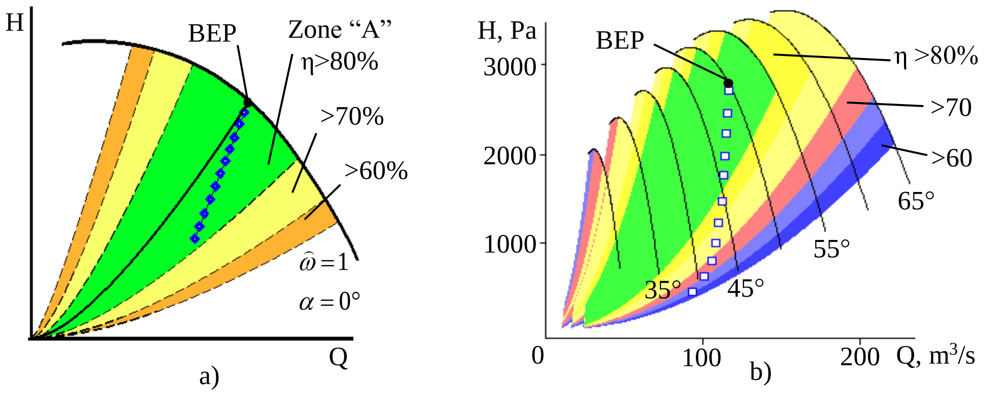


Fig.6. Constant efficiency zones for centrifugal – a) and axial-flow fan – b)

Table 1

Comparison of speed and combined methods of the fan control

Operating Point	Speed control, $\alpha = 50°$		Combined control			Efficiency difference	
	η_1, %	Speed, p.u.	η_2, %	Pitch angle, α	Speed, p.u.	Absolute	Relative
1	57.6	0.64	66.8	65	0.44	+9.2	+16.0
2	62.9	0.69	71.0	65	0.48	+8.1	+12.9
3	67.4	0.73	74.2	65	0.52	+6.8	+10.1
4	72.5	0.76	77.3	65	0.55	+4.8	+6.6
5	77.1	0.80	80.1	60	0.64	+3.0	+3.9
6	80.1	0.84	82.0	55	0.74	+1.9	+2.4
7	83.3	0.88	84.2	55	0.79	+0.9	+1.1
8	84.8	0.91	85.0	55	0.82	+0.2	+0.2
9	86.0	0.94	86.0	50	0.94	0	0.0
10	86.6	0.97	86.6	50	0.97	0	0.0
11	87.0	0.99	87.0	50	0.99	0	0.0

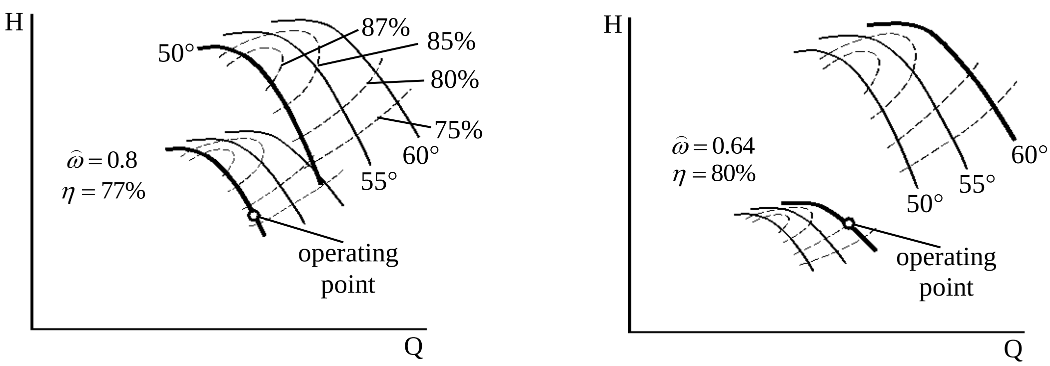


Fig.7. Maximum efficiency search at a given operating point by changing a pitch angle and a shaft speed

Energy loss minimization in a frequency variable drive system

Steady state mode of operation

Additional energy savings in the ventilation system can be realized on the basis of extremum control algorithms which are capable to provide required mode of fan operation along with simultaneous minimization of steel and copper energy losses in a motor which dependence on flux linkage is featured with explicit minimum. Optimum drive control may be implemented with different methods [2, 3, 4], for instance with loss model-based method which however is vulnerable to uncertainty and no stability of the motor parameters. The paper deals with on-line iterative method of searching the minimum of overall energy losses which is insensitive to fluctuations of the motor parameters and is capable to minimize total drive energy losses.

Loss minimization problem has been studied with assistance of mathematical and computer model of an induction machine (IM) in the form of differential equations, which took into account separate impacts of eddy current and hysteresis phenomena on nonlinear magnetization processes [5]. Simulation has been carried out in Matlab Simulink environment using parameters of the induction motor of P = 315 kW, U = 660 V, R1 = 0,012 Ω, R2 = 0,014 Ω, L1σ = 3,1·10-4 H, L2σ = 3,4·10-4 H, Rμ = 280 Ω, Lμ = 0,018 H. Drive mechanical load is defined by a ventilator-related characteristics for which torque M and power P are varied as follows: $M = M_0 \cdot \hat{\omega}^2$ and $P = P_0 \cdot \hat{\omega}^3$. In this case of scalar control, voltage U and frequency f of VSI vary due to the law: $(U/f^2) = const$ .In order to find the function extremum, a set of curves "energy losses P_t versus flux linkage Ψ_m" has been obtained within the motor angular velocity range $0.5 \le \hat{\omega} \le 1$. Typical graph $P_t(\Psi_m)$ (fig.5a) shows that at $\hat{\omega} = 0.8$ minimum of energy losses takes place at $\Psi_m = 0.52 \cdot \Psi_{m0}$, where Ψ_{m0} is a rated value. Optimal control law corresponds to line 1 (Fig 5.b), which connects extremum points of curves $P_t(\Psi_m)$ for different values of the motor speed. Line 2 reflects energy losses according to the scalar drive control law: $(U/f^2) = const$.

Usage of the optimal control law allows for decreasing in total energy losses by 5-10% as compared to traditional scalar drive control algorithm. Structure of the control system minimizing total drive energy losses is presented in Fig.9a. The control system is to keep the motor speed constant, to monitor the input power and to search for a function extremum through changing VSI output voltage due to formula: $\Delta U(i+1) = U(i) + k \cdot \Delta U$, $k = 1,\ if\ \Delta P_i < 0$ and $k = -1,\ if\ \Delta P_i > 0$, where ΔP_i and ΔU_i are increments of power and voltage at step i of extremum search process.

As it is seen from results of simulation (Fig.9.b), interval of time 20 s to find the extremum is significantly less than time span between two possible changes of the drive mechanical load.

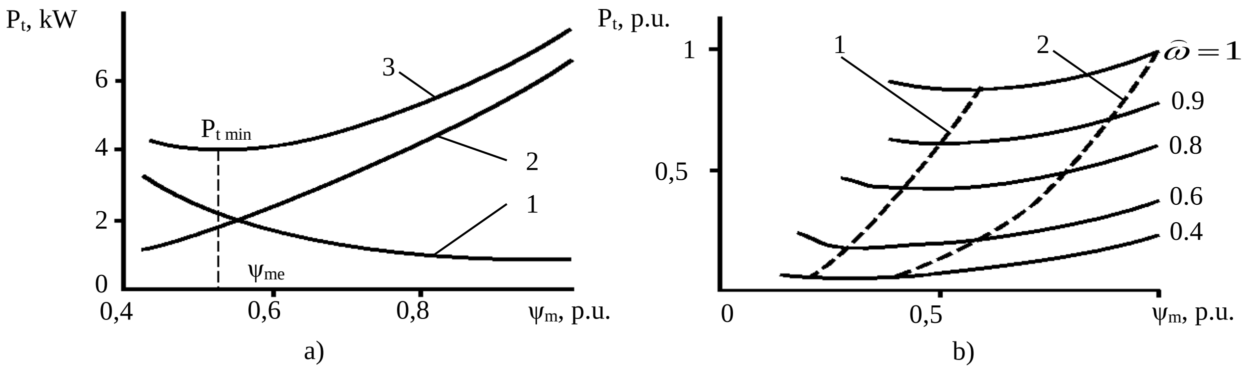


Fig.8. Variations of steel loss (1), copper loss (2) and total losses (3) versus flux linkage – a) and total losses variation under optimal control (1) and traditional scalar control (2) – b)

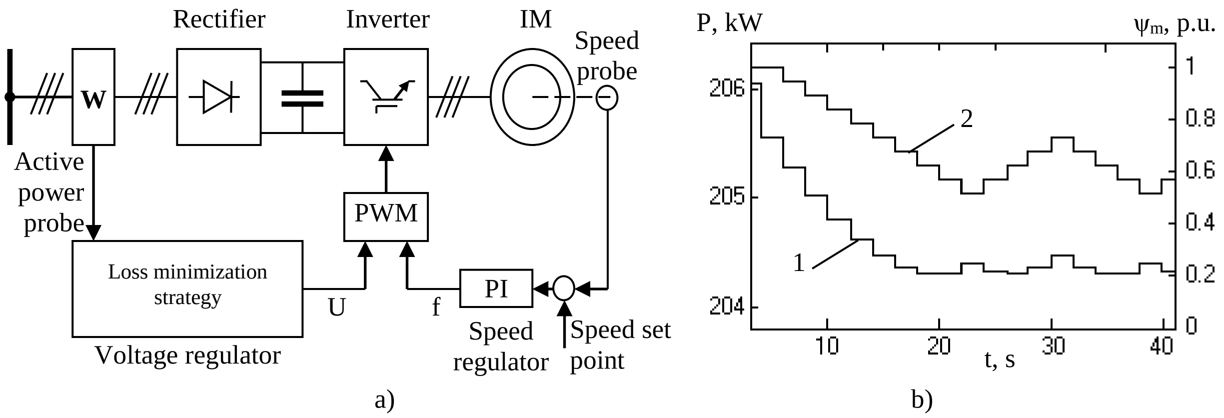


Fig.9. Structure of the control system based on a searching algorithm – a) and variations of power consumption (1) under changing the motor flux linkage (2) – b)

Energy savings on improvement of drive-mains compatibility

Energy loss and voltage drop minimization while starting up the motor

When a fan motor is started using across-the-line technology, inrush current (up to six times the rated value) is created causing voltage drops and additional energy losses in lines. To avert brown out conditions, soft starters and VFD technology is used to reduce an extreme peak of current draw. Minimization of energy and voltage losses under start-up conditions may be achieved through finding start-up motor control law meeting following requirements [6]:

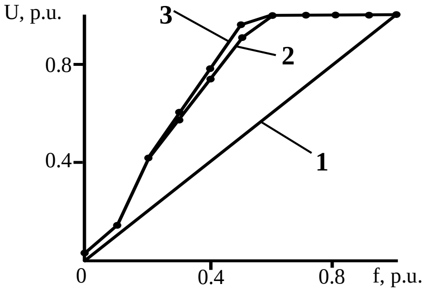
$$W_{st-l} = \int_0^{t_s} P_t(t)dt \to \min ,$$
$$J_{\Delta u} = \int_0^{t_s} \left(|E| - |U_{dr}|\right)^2 dt \to \min \qquad (5)$$

where P_t (t) – variation of power loss while starting up the motor, W_{st-l} – start-up energy losses, E – no loaded mains voltage, U_{dr} – current voltage value.

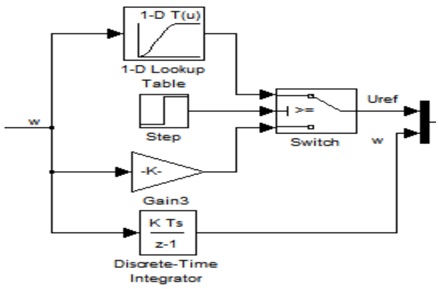
On the basis of optimization methods and Matlab tools the relationship between frequency vector $\hat{f} = [0, 0.05, 0.1, ...1]^T$ and motor voltage vector

$\hat{U} = [0, \hat{U}_1, \hat{U}_2, ...U_{20}]^T$ has been established using conditions (5). Here $\hat{f} = f / f_0$, $\hat{U} = U / U_0$, f_0 and U_0 are rated values of frequency and voltage.

Graph representation of obtained start-up control laws is given in Fig.10a. It is seen that meeting requirements (5) to minimize energy losses and voltage drop results in deriving similar control laws 2 and 3 which are however different from commonly used linear control law 1.



a)



b)

Fig.10. Graphs of optimized (curves 2,3) and traditional start-up control laws – a) and their MATLAB realization –b)

Optimal start-up control law was realized with a look-up table block which implements linear interpolation of discrete set of points. After termination of start-up mode of operation, optimal steady-state loss minimization control law is applied.

As it seen from simulation results (Fig.11) application of optimal start-up control law ensures less voltage drop and less values of active and reactive power consumption than traditional linear control law. Decrease in energy consumption is of 30%, in voltage drop – 7%.

Energy savings on mine reactive power compensation by active rectifier as a fan VFD component

Application of active front end technology [8] in building-up the frequency variable drive submits a lot of benefits for controlling both motor-related and grid- related processes. Depending on control algorithms applied and current capacity an active rectifier can stands for such devices as VAR compensator, voltage regulator, active power filer and three-phase voltage asymmetry compensator [9].

It was shown earlier that mine fan and VFD is normally oversized at initial stages of fan operational cycle. So, there is opportunity to use drive active rectifier for generating reactive power to compensate for inductive reactive power of the mine power station load. Potential of reactive power Q_{VAR} that could be generated by AR under conditions that apparent power S is kept constant is determined as follows $Q_{VAR}(t) = \sqrt{S^2 - P(t)^2}$. Potential of AR as a VAR compensator over operational cycle of centrifugal fan with VFD of $S = 2\,MVA$ is shown in Fig. 12.

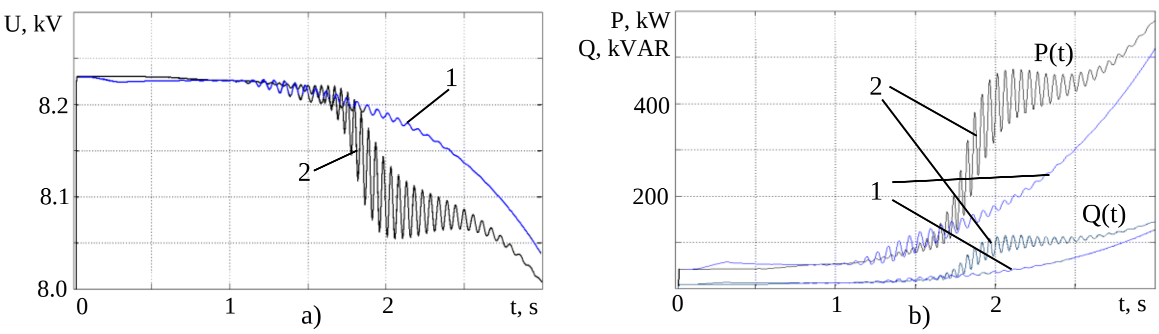


Fig.11. Voltage – a), active P(t) and reactive power Q(t) – b) transients for optimal (1) and linear start-up control law (2)

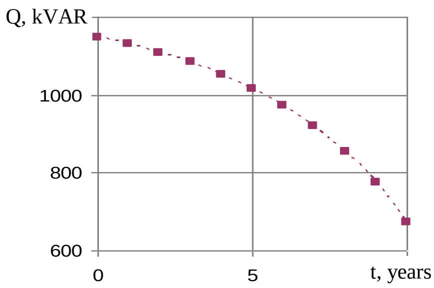


Fig.12. Potential of the drive reactive power over fan 10-year operational cycle

Topology of AR is similar to that of VSI and control algorithms are practically the same. An analogue of the drive vector control algorithm (Fig. 13a) comprises $abc \leftrightarrow dq0$ transformations, separate regulation of DC-link voltage and reactive power via producing u_{dm}, u_{qm} and then u_{am}, u_{bm}, u_{cm} PWM modulating voltages by means of PI-regulators under conditions that I_d – component coincides with a generalized voltage vector.

Operation of AR as VAR compensator has been simulated by means of SimPower BlockSet elements which were used to create a model of the system “mains – mine power distribution network with loads - active rectifier as an input component of the mine fan VFD”. Load reactive power profile of one of the “Vorcuta-ugol’ company” mines is presented in Fig. 13b. The problem was to ensure constant value of reactive power at level of $Q_{VAR} = 200\,kVAR$. Results of simulation (Fig 13b) show that under keeping the drive active power constant (curve 4) the AR generates variable in time amount of reactive power (3) that is enough to compensate for inductive reactive power of the mine load (1) and keep the resultant VAR power at a set value. Fluctuations of reactive power (2) are due idealized step-wise form of curve 1. It should be noted that multilevel implementation of AR and VSI allows eliminating the need of isolation transformers in medium voltage drives and providing related savings on capital and site construction costs.

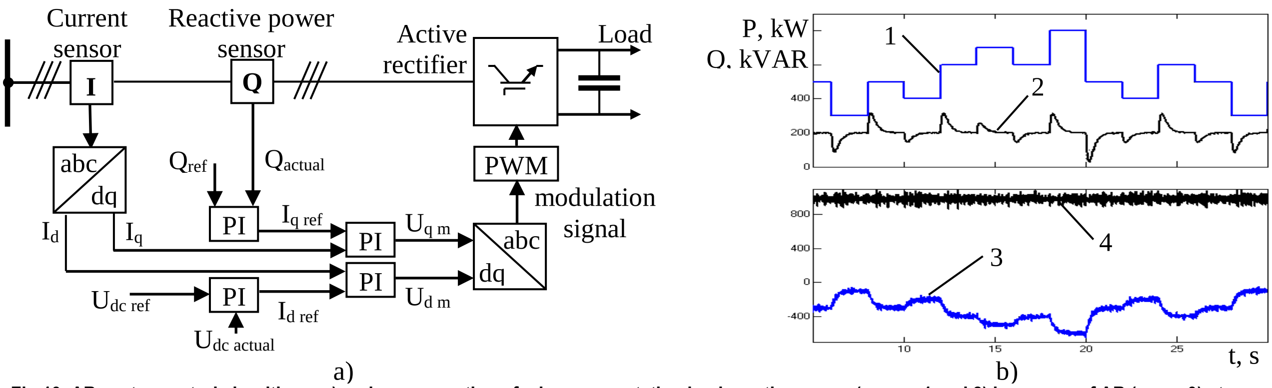


Fig.13. AR vector control algorithm – a) and compensation of mine power station load reactive power (curves 1 and 2) by means of AR (curve 3) at keeping the drive active power constant (curve 4) – b)

Conclusion

1. Systems approach has been applied to reveal and capture opportunities of energy savings in mine ventilation systems. Basic potential in the ventilation system efficiency increase is connected with realization of VOD concept via application of VFD for a main mine fan with multipurpose control subsystem integrated in an overall mine process control system. VFD control system is designed to minimize energy losses at different points of energy flow from the mains to working places of the mine.
2. On the basis of performance characteristics of centrifugal and axial-flow fans, various modes of operation have been investigated to substantiate high efficiency speed control and combined control methods for providing sufficient air flow on both a day demand and fan operational cycle demand.
3. On the basis of drive simulation it was shown that minimization of total drive energy losses in steady state mode of operation can be achieved through application of on-line iterative method of searching an extremum of the energy loss function. This gives benefits of 5-10% energy savings as to traditional scalar controlled drive. In a start-up operational mode energy savings are shown to be due to application of optimal control law which simultaneously ensures minimization of voltage drops.
4. Results of drive simulation have proved the functionality of active rectifier in capacity of VAR compensator of reactive power of mine distribution network. In case of multilevel implementation of the drive frequency converters, additional benefits come from exclusion of isolation step-down transformer from power supply circuit.

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