Methodology for comparing the energy efficiency of methods for regulating the performance of a blower station

Maksim Vecherkin¹*, Anvar Sarvarov¹ and Irina Romanova¹

¹ Magnitogorsk State Technical University named after G.I. Nosov, 455000, Magnitogorsk, Russian Federation

*Corresponding author e-mail: vecherkin@inbox.ru

Abstract. A methodology for comparing the energy efficiency of different methods of regulating the total productivity of a blower station is presented. The basic principles of electrical modeling of duct networks are shown for the mathematical description of their properties and characteristics. The results of a comparison of the energy efficiency of regulating methods for a single fan and a group of five fans operating on a common line are presented. The conclusion about the high energy efficiency of the combination of start-stop control with smooth control using axial guide vanes for a blowing station of five fans is obtained.

1. Introduction

Blower stations are a group of fans working in parallel on a common line to supply air to various process facilities. In most cases the fans are fitted with high-voltage induction motors. These drives are initially designed as unregulated, making it impossible to vary the performance of the fans to the needs of the operation. This leads to overconsumption of electricity, which in some cases can be as high as 30% [1]. Reduction of unjustified power consumption is possible by adjusting the fan performance depending on the production needs. Consider a fan station with five fan units operating on a common main line and supplying air to three consumers of the same type (figure 1) [2].

Figure 1. Structure of the blower station.
Each of the five fans generates the corresponding pressure $H_1$-$H_5$ and ensures the performance of $Q_1$-$Q_5$. From a common line, air is distributed to consumers, each of which has the ability to individually control the air flow rate by valves. In front of the valves of each consumer, pressures $H_1$-$H_3$ are created, the values of which should ensure the functioning of each consumer independently of the others. Thus, the blower station must provide performance in accordance with the required total flow rate, and also create pressure in front of consumers not less than the specified permissible values. In general, the following methods of regulating the total capacity of the blower station are possible:

1) change of the network resistance by means of shut-off valves on the blower discharge side – throttling;
2) changing the speed of rotation of the fans – frequency control;
3) change in the number of operating fans – start-stop regulation;
4) changing the angle of rotation of the blades of the axial distributor of the fans – inlet-vane control;
5) a combination of two different methods – combined regulation.

The listed methods of regulation are not equivalent to each other both in terms of energy efficiency and in terms of material costs required for their implementation.

The most effective way is the frequency control of the fans. For its implementation, it is necessary to equip fan electric drives with frequency converters. However, the high cost of high-power high-voltage inverters prevents their widespread use. For fan stations, in most cases, the payback period of high-voltage inverters exceeds their service life [1].

Throttling is a standard means of regulating the air flow for each individual consumer. However, when fans are throttled, this method has low energy efficiency, which is confirmed by numerous theoretical and experimental studies [1, 3, 4].

Changing the angle of rotation of the axial distributor is essentially a throttling on the air intake side of the fan. The blades of the axial distributor then twist the air flow, which provides better control characteristics compared to throttling on the discharge side. For automatic regulation of the fan performance, it is necessary to equip the axial distributor with actuators that provide both the angular movement of the blades and the control of the angle of their rotation.

Start-stop regulation allows you to change the total performance in steps by changing the number of fans in operation. The implementation of this method requires the use of soft starters that neutralize the negative consequences of direct starting of powerful induction motors [2].

Combined regulation can be realized by a combination of different methods: frequency and inlet-vane control, start-stop and throttling, etc.

The problem is the choice of one method or another in each specific case, taking into account the characteristics of the technological object. In most cases, an experimental way of choosing a control method is impossible. It is rational to solve this problem theoretically, on the basis of research of a mathematical model describing the operation of fans and a network of air ducts.

2. Materials and methods

Two main approaches can be identified for comparing the energy efficiency of fans regulation: the graphical method and the electrical modelling method.

The graphical method has been developed in detail for single fans [1, 3, 5]. It makes it possible to determine any of the values required for a comparative analysis from the fan specifications and the known network parameters. Such values are: pressure $H$ and productivity $Q$ of each fan, mechanical power $P$ on the motor shaft, efficiency $\eta$ of fan. The advantage of the graphical method is clarity. A significant disadvantage of the method is the complexity of its implementation for a group of several fans [3].

The electrical simulation method is based on the analogy between the physical processes of electric current flow in branched circuits and air movement in duct networks. The different parts of the ventilation network are represented as equivalent electrical elements [6]. This makes it possible to represent any complex duct network as a virtual substitution network and to analyse it using Kirchhoff equations.

The work is based on the electrical modelling method. The basic principles of electrical modelling of ventilation networks are described in special literature [7]. The fan performance or air flow $Q$ is equivalent to electric current, pressure $H$ is equivalent to voltage, aerodynamic network resistance $R$ is equivalent to electric resistance. The method is based on two obvious conditions: the balance of flow rates at nodes and the balance of pressure losses in closed loops. These conditions for a network without backpressure are written in general terms as follows:
\[
\begin{align*}
\sum_{j=1}^{n} Q_j &= 0 \\
\sum_{i=1}^{m} H_j &= \sum_{i=1}^{l} R_i - Q_i^2
\end{align*}
\]

(1)

where \(Q_i\) is the air flow through the network section; \(R_i\) is the aerodynamic resistance of the section; \(H_j\) is the pressure created by the fan in the closed circuit; \(n\) is the number of nodes in the circuit; \(m\) is the number of fans operating in the closed circuit; \(l\) is the number of sections with pressure losses in the circuit.

The difference between equations (1) and Kirchhoff's laws is that in the second equation the flow \(Q\) (current equivalent) enters in the second degree.

Based on the above, the duct network in figure 1 can be represented by the equivalent diagram in figure 2.

The resistors in the diagram simulate the aerodynamic resistance of the network sections, the variable resistors are valves, the voltage sources are fans.

\[
\begin{align*}
Q_1 + Q_2 + Q_3 + Q_4 + Q_5 &= Q_1 + Q_2 + Q_3 \\
Q_1^2 R_1 - Q_2^2 R_2 &= H_1 - H_2 \\
Q_2^2 R_2 - Q_3^2 R_3 &= H_2 - H_3 \\
Q_3^2 R_3 - Q_4^2 R_4 &= H_3 - H_4 \\
Q_4^2 R_4 - Q_5^2 R_5 &= H_4 - H_5 \\
Q_5^2 R_5 &= H_5 - H_6 \\
Q_1^2 R_1 + Q_2^2 R_2 &= H_1 - H_1 \\
Q_2^2 R_2 + Q_3^2 R_3 &= H_1 - H_2 \\
Q_3^2 R_3 + Q_4^2 R_4 &= H_2 - H_3 \\
Q_4^2 R_4 + Q_5^2 R_5 &= H_3 - H_4 \\
Q_5^2 R_5 &= H_4 - H_5 \\
Q_1^2 R_1 + Q_2^2 R_2 &= H_5 - H_6 \\
Q_2^2 R_2 &= H_6 - H_2
\end{align*}
\]

(2)

In real networks, the air pressures in the individual sections are often known and are determined from instrument readings. Usually the pressures upstream of the valves at points \(a\), \(b\) and \(c\) (figure 1) are monitored, which is necessary for the functioning of metering and automatic control systems. Therefore, in equation system (2) the pressure drop at the valves is replaced by the corresponding pressures upstream of the valves \(H1, H2, H3\).
The given system (2) cannot be solved in general terms. In order to implement numerical calculation methods it is necessary to set the air flow rates of consumers $Q_1, Q_2, Q_3$, the aerodynamic resistances of all network sections $R_1, R_2, R_3, R_1-R_5$, the pressures before the valves of each consumer $H_1, H_2, H_3$. The unknowns are the capacities $Q_1-Q_5$ and the pressures $H_1-H_5$ of each fan.

The system of non-linear equations (2) has many solutions, most of which are unacceptable. These are, for example, solutions with negative values for the fan capacities or airflow rates of the consumers. In order to exclude these solutions, the condition of equal fan capacities must be set:

$$Q_1 = Q_2 = Q_3 = Q_4 = Q_5$$

(3)

This condition provides a single solution to system (2), corresponding to the same positive performance values of all fans. In addition, condition (3) facilitates the search for the optimal, according to the criterion of minimum energy consumption, operating modes of the fans.

Fan performance and pressure are the main parameters that determine the fan's operating mode. The aerodynamic characteristics can be used to determine all the main energy parameters of the fan: effective power, mechanical power on the motor shaft, fan efficiency.

Aerodynamic characteristics are graphical dependencies of pressure on capacity, mechanical power on the fan shaft on efficiency and the fan efficiency on performance. These characteristics can be approximated with sufficient accuracy for engineering calculations by functions [3]:

$$H = a_1 Q^2 + b_1, \omega Q + c_1, \omega^2$$

(4)

$$P = a_2 Q^2 + b_2, \omega^2 Q + c_2, \omega^3$$

(5)

$$\eta = \frac{QH}{P} = \frac{a_1 Q^3 + b_1, \omega Q^2 + c_1, \omega^2 Q}{a_2 Q^2 + b_2, \omega^2 Q + c_2, \omega^3}$$

(6)

where $H$ is total pressure of the fan; $Q$ is performance; $P$ is power at shaft; $\omega$ is motor speed; $a_1, b_1, c_1, a_2, b_2, c_2$ are coefficients depending on the blade angle of the axial distributor.

In order to obtain functions which enable analysis for all control methods, it is necessary to consider the dependence of the coefficients $a_1, b_1, c_1, a_2, b_2, c_2$ on the blade angle of rotation of the axial distributor. These dependencies may be represented in the form of analytical functions or by means of spline interpolation of data.

Thus, the system of equations (2) together with the condition (3) and approximating expressions (4)-(6) represent a mathematical model that allows analyzing various operation modes of the blower station in a wide range of performance changes at various control methods.

3. Results and discussions

Based on the presented mathematical model, a methodology for comparing the energy efficiency of control methods has been created. The essence of the methodology is as follows:

1. An equivalent electrical substitution diagram is created from the drawings of the duct network. The parameters of each circuit element are determined using the reference data.
2. A system of equations describing the electrical substitution diagram is compiled according to the rules (1).
3. The coefficients of polynomials (4)-(6) and their dependence on blades' angle of rotation are determined according to the known aerodynamic characteristics of fans: $a_1(\alpha), b_1(\alpha), c_1(\alpha), a_2(\alpha), b_2(\alpha), c_2(\alpha)$.
4. Set the values of the air flow of each consumer $Q_1, Q_2, Q_3$ and their corresponding pressures $H_1, H_2, H_3$, based on the actual needs of the process facility.
5. The system of equations (2) is solved numerically. The unknowns in the system are the pressures $H_1-H_5$ and capacities $Q_1-Q_5$, which determine the operating points of the fans on the flow and pressure characteristics.
6. Calculate the regulator parameters corresponding to the operating points for the different capacity control methods:
   a) Aerodynamic damper drag (at nominal fan speed and open axial distributor);
   b) Fan speed (at open throttle and open axial distributor) as the positive root of equation (4)

$$\omega = -\frac{b_1 Q + \sqrt{(b_1 Q)^2 - 4c_1(a_1 Q^2 - H)}}{2c_1};$$
c) angle of rotation of the axial distributor blades (at rated fan speed and open throttle).
7. The power input (5) and efficiency (6) for each control method are calculated from the known operating points of the fans and the parameters of the controllers.
8. Steps 4-7 are repeated for different values of airflow by consumers.
9. Based on the results of the calculations, the following dependencies are plotted:
   a) plots of the total power consumed by the blower station versus the total performance;
   b) graphs of efficiency versus performance for each fan.
10. A comparative analysis is made of the power input and the efficiency for the operating conditions of the fans, the advantage of one or the other control method in terms of energy efficiency is concluded, and the limits for the acceptable fan performance ranges are evaluated. The limits of the ranges are determined by the value of the minimum allowable efficiency, which for the fans is equal to

   \[ \eta_{\text{min}} = 0.9 \eta_{\text{max}} \]  

   where \( \eta_{\text{max}} \) is the maximum efficiency of the fan corresponding to the nominal performance.

Let's consider possibilities of this methodology with reference to single fan operation on a network without counter-pressure with unchanged parameters. The fan has high-voltage asynchronous electric drive with rated power 800 kW and aerodynamic characteristics typical for centrifugal fans [8]. Figure 3 shows the calculated dependencies of power consumption (figure 3, a) and efficiency factor (figure 3, b) in relative units at different methods of fan regulation (\( P \) – power, consumed by fan installation to create productivity \( Q \), \( P_n \) – power, corresponding to the nominal performance \( Q_n \)). The graph for frequency control is shown with a typical frequency converter efficiency of 0.95.

The calculated dependencies in figure 3 show that for a single fan the frequency control has an advantage over other methods over a wide performance range. These results are in agreement with numerous theoretical and experimental studies, which confirms the validity of the methodology.

![Figure 3](image_url)

**Figure 3.** Calculated energy data for single fan operation: a – relative fan capacity from relative performance; b – Fan efficiency from relative performance.

Frequency control and intel-vane control are comparable in terms of energy efficiency with a small control range near the nominal capacity values. The advantage of frequency control is constant fan efficiency over the entire performance range (figure 3, a). Throttling has little effect on fan efficiency (figure 3, b), but is significantly inferior to other methods in terms of power consumption. However, the results obtained for a single fan cannot be generalised to the case of a group of fans running in parallel on a common line. Figure 4 shows the graphs for frequency control of five fans and combined control by changing the number of running fans in combination with intel-vane control. The graphs are plotted for the case of simultaneous fan control, provided condition (3) is met.
Figure 4. Calculated energy data for a group of fans: a – the relative total power of the blowing station from the relative total productivity; b – efficiency of one fan versus the relative performance of one fan.

The graphs show that when five fans are controlled simultaneously, frequency control has no advantage over intel-vane control in terms of power consumption. The advantage of intel-vane control increases when the combined control is used for small total performance. Turning off part of the fans both reduces the power input (figure 4, a) and increases the efficiency of the operating fans (figure 4, b).

4. Conclusions

The electrical modelling method is an effective tool for analysing ventilation networks. A mathematical model based on an equivalent electrical model and a mathematical description of the fans is a powerful tool for finding energy-efficient modes of operation for blower stations. The given modeling technique allows solving a wide range of tasks related to fan operation in branched networks: analysis of energy efficiency of different performance modes; selection of fans for a network with given parameters; determination of pressure and flow values in separate sections; optimization of ventilation network operation [9], etc.

Examples of application of the methodology show that the established ideas about the advantage of frequency control of asynchronous electric drives are not always true for a group of fans running in parallel. In the case considered, frequency control loses out in terms of energy efficiency to the combined control method. This is not a general conclusion for all blower units. For each case, an analysis of the mathematical model is necessary, taking into account all relevant properties of the object in question [10].

The presented methodology can be adapted for other energy intensive technological objects: compressor, gas blower [11] and pumping stations taking into account the peculiarities of these objects.

5. References

[1] Leznov B.S. 2006 Energy saving and variable electric drive in pumping and blowing installations. (Moscow, Energoatomizdat), 360 p.
[2] Vecherkin M.V., Sarvarov A.S. 2006 Study of methods to regulate the productivity of the fan station of Sheet Rolling Mill №10 of OJSC "Magnitogorsk Iron and Steel Works», Electromechanics, Vol. 62, №4, pp 63-67.
[3] Vahvahov G.G. 1975 Operation of the fans in the network (Moscow: Strojizdat), 101 p.
[4] Onishchenko G.B., YUn'kov M.G. 1972 Turbomachinery electric drive (Moscow: Energiya), 240 p.
[5] Vahvahov G.G. 1989 Energy saving and reliability of fan systems (Moscow: Strojizdat), 176 p.
[6] Glikman B.F. 1986 Mathematical models of pneumohydraulic systems (Moscow: Energiya), 368 p.
[7] Abramov F.A., Bajkov V.A., Frolov I.A. 1961 *Electrical modelling of mine ventilation networks* (Moscow, Gosgortekhizdat), 136 p.

[8] Solomahova T.S., Chebysheva K.V. 1980 *Centrifugal fans. Aerodynamic diagrams and characteristics: Handbook*, (Moscow: Mashinostroenie), 176 p.

[9] Himla J.W. 2009 *Optimized fan control in variable air volume HVAC systems using static pressure resets: strategy selection and savings analysis*, (Texas A&M university) – Thesis for master of science degree. 70 p.

[10] Krupnikov A.V., Vanyashov A.D., Yanvaryov I.A. 2010 *Analysis of efficiency of air coolers on the basis of units with various number of fans* (Omsk: Omsk State Technical University) The Journal Omsk Scientific Bulletin №3 (93), pp 173-176.

[11] Kryachuk V.M., Vecherkin M.V., Shpon'ko A.A. 2011 *Diagnostics of Gas Blowers at OJSC "Magnitogorsk Iron and Steel Works" Coke Plant*, (New York: Allerton Press, Inc.), Coke and Chemistry, Vol. 54, №12, pp. 484-488.