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Automation and control of blow moulding mechanisms according to the criterion of maximum energy efficiency

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Abstract. The article presents the control algorithms that allow to increase the energy efficiency of the metallurgical production facilities' blow molding mechanisms by impacting on the actuating elements of electrical engineering complexes. A mathematical model is proposed that allows the calculation of energy efficiency. It is shown that this effect is achieved due to: a systematic approach to the design of electrical systems; the use of new types of electric machines; selection of control and regulation algorithms; transition of unregulated control systems to adjustable electric drives; rational choice of elements of electrical systems; increasing the level of staff skills. Energy efficiency assessment was performed for the object, which proposed the mutual influence of the elements of the system. The proposed control laws were compared with systems based on unregulated electric drives and structures in which the air flow was controlled by the guide vanes. It has been established that while transitioning to new control algorithms, it is possible to reduce losses in the system by about 35%.

1. Introduction

A modern electric drive serves very different technological processes and mechanisms that differ in the nature of movement, efficiency, purpose, power, accuracy of movement, environmental conditions, etc. Technical solutions embedded in the current electric drive often reflect the capabilities of past years and are also characterized by great diversity.

All this leads to the fact that the possible ways of energy saving in the electric drive are diverse, ambiguous, as indicated by the options shown in figure 1.

2. Problems and ways of energy saving in electric drive

In [1], the energy performance of the electric drives of a fan or a smoke exhauster without considering their mutual influence was considered. However, in real conditions, these BMM have a common gas-air path through which their interaction takes place [2]. For this reason, it is quite natural, even necessary to take into account this interaction.

The essence of the task is most clearly illustrated by a plot (figure 2), where the horizontal axis represents the aerodynamic resistance *R* of the gas-air duct of the boiler, and the vertical axis shows the pressure drops along the gas-air duct, as well as those created by the fan and the smoke exhauster [3]. A fan is installed along this path (dashed vertical line B - B in figure 2), which creates an overpressure at the inlet of the path, the exhaust fan (dashed vertical line D - D in the same figure), which creates a negative pressure drop. In addition, to measure the degree of rarefaction in the furnace space, a draught and pressure gauge is installed (it corresponds to the vertical T - T in figure 2) [4].

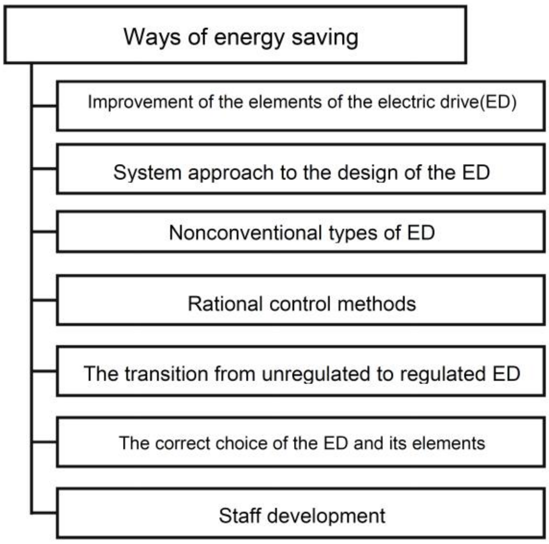

Figure 1. Problems and ways of energy saving in electric drive.

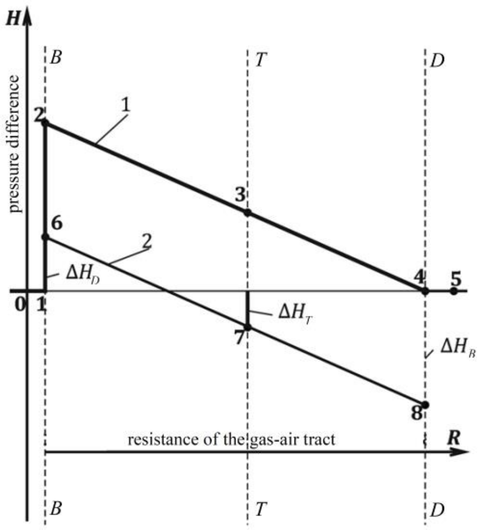

Figure 2. Diagrams of the pressure distribution of the gas-air duct of the boiler.

As an initial variant, let us consider the case when the gas-air path of the boiler is completely balanced (for example, with a cold non-operating boiler), and only the electric drive of the fan is turned on [5]. This case corresponds to a broken line 0-1-2-3-4-5: first, a fan creates an overpressure surge (segment 1-2), which evenly drops to the outlet to zero (straight line 2-3-4). The inclination of this straight line for the existing gas-air duct is greater, the greater the flow rate [6]. The magnitude of the initial pressure jump 1-2 is created and regulated by the fan, and the slope of the straight line 2-3-4 is determined by the flow rate.

In accordance with the technical requirements for the operation of the boiler [7] at the point T, a pressure gauge is installed and at this point it is necessary to create a negative pressure $\Delta H_T = -30$ Pa.

The slope of a straight line 2-3-4 for the existing gas-air tract and a given flow rate cannot be changed [8], therefore, in order to obtain the required amount of vacuum at point T, it is necessary to displace the straight line 2-3-4 parallel to itself until the required differential ΔH_T (broken line 0-1-6-7-

8-4-5). For this it is necessary: first, to reduce the pressure drop created by the fan by any of the known methods [9], and second, to create a negative differential (additional vacuum) at point D, where the exhaust fan is installed [10].

At the same time, if the air flow rate does not change, then the difference in height between points 2 and 4, as well as 6 and 8 remains unchanged [11].

The magnitude of the head on the fan side and the vacuum on the side of the exhaust fan cannot be chosen arbitrarily but must be such as to keep the height (depth) of point 7 above (below) the horizontal axis unchanged [12].

The position of point T along the horizontal axis depends, firstly, on the installation site of the gas stopper [13] and, secondly, on the design of the gas-air duct and the installation site of auxiliary equipment (for example, additional heat exchangers, etc.) [14].

So, from the position of the point T on the R axis, the horizontal offset of a 2-3-4 (or 6-7-8), i.e. the degree of mutual influence of the fan and exhaust fan. But in practice, the exact position of the point T on the R axis is difficult to determine [15].

In this regard, we draw attention to the following circumstance, noted during experimental studies. On DE boilers, the value of the aerodynamic resistance of the gas-air duct is much less than the resistance of regulating devices (gate valves, guide vanes) [16]. Therefore, we can assume that the energy performance of electric drives BMM, calculated during autonomous operation of units for a certain fixed value of consumption, will remain the same when working together.

3. Mathematical model

To verify this, we compared the calculations for the aerodynamic characteristics of the VDN-9 fan and the DN-11.5 smoke exhauster and the experimental results of measurements of the electric power consumption of these units in one of the actual operating modes of the DE-16-14 boiler [17], when the gas flow rate $Q_G = 500$ m^3/h. The performed calculation is given in Example.

Determine the energy performance of electric drives and mechanisms of the boiler DE-16-14 with the joint operation of the fan VDN-9 and the DN-11,2 smoke exhauster. The gas flow rate $Q_G = 500$ m^3/h, the coefficient of excess air $K_{EXC} = 1.281$ [18]. The results of additional experimental measurements of the same mode of operation of the boiler are given in [19].

Total air flow $Q = K_{GIV} \cdot K_{EXC} \cdot Q_G = 10.5\ 1.281 \cdot 500 = 6700$ m^3/h = 1.9 m^3/s. According to the aerodynamic characteristics of the fan VDN-9 [20], we find $H = 3400$ Pa with $Q = 1.9$ m^3/s. Aerodynamic fan power $P_{FAN} = H \cdot Q = 3400 \cdot 1.9 = 6.5$ kW. Active electric power consumed by the fan electric drive from the network [21], measured during the experiment $P_{ACT} = 10.2$ kW. Taking the motor efficiency $\eta_E = 0.9$, we obtain the value of the power on the fan shaft: $P_{SHAFT} = P_{ACT} \cdot \eta_E = 10.2 \cdot 0.9 = 9.2$ kW. As a result, the fan efficiency $\eta_{FAN} = P_{FAN} / P_{SHAFT} = 6.5 / 9.2 = 0.71$.

On the aerodynamic characteristics of the fan VDN-9 [22] for the same pair of flow and pressure values, we have $\eta \approx 0.7$, which almost coincides with the results of the calculation based on experimental baseline data. Let's carry out similar calculation for the DN-11,2 smoke exhauster. According to the aerodynamic characteristics of the exhauster [23] at $Q = 1.9$ m^3/s, we find $H = 3300$ Pa. Aerodynamic power of the exhaust fan $P_{EXH} = H \cdot Q = 3300 \cdot 1.9 = 6.3$ kW.

The active electric power consumed by the electric drive of the exhauster from the network [24], measured during the experiment, $P_{ACT} = 19.1$ kW.

Taking the engine efficiency $\eta_E = 0.8$ (which is slightly lower than the nominal value due to underload), we obtain the amount of power at the exhauster shaft: $P_{SHAFT} = P_{ACT} \cdot \eta_E = 19.1 \cdot 0.8 = 15.3$ kW. As a result, the efficiency of the exhaust fan $\eta_{FAN} = P_{FAN} / P_{SHAFT} = 6.3 / 15.3 = 0.4$.

On the aerodynamic characteristics of the DN-11.2 smoke exhauster [25] for the same pair of flow and pressure values, we have $\eta \approx 0.5$. Discrepancies in the efficiency of the exhaust fan, obtained in different ways, there are, but their value is quite acceptable for estimated calculations.

So, the given example gives the basis to perform energy calculations in BMM electric drives when the fan and the smoke exhauster work together as well as when they work separately. This allows, firstly, to simplify the calculations themselves, and secondly, to use the techniques described in this article.

4. Automation of the control of the blow molding mechanisms and the comparison of losses under various laws of regulation

Solving the problem of minimizing the electric power consumption by BMM electric drive, it is necessary to ensure the specified thermal performance of the boiler, which can vary within certain limits. At the same time, different ways to control the performance of the boiler have different possibilities for minimizing power consumption. When regulating the flow valve, you can change the performance of the boiler, but from the point of view of power consumption, this is the most energetically disadvantageous method due to large power losses at the valve. There are no ways to reduce losses in BMM and their electric drives. When regulating the flow effect on the blades of the guide vane, you can achieve savings. This follows from [26]. However, for centrifugal BMM this gain is negligible and for the boiler DE-16-14 when the flow rate changes in the range Q = 2…3 m^3/h does not exceed 2…4 kW.

The greatest reserves of savings are observed in schemes with regulation of the angular velocity of BMM with the help of modern electric drive systems (for example, with frequency regulation of the speed of an asynchronous electric drive). Here two directions of energy saving should be considered. First, the losses in the gas-air channel are reduced, since flow control is advisable to keep with fully open dampers and the optimum angle of rotation of the blades of the guide vane, so that the resistance of the gas-air channel to the movement of air is minimal. The second direction of reducing losses in the electric drive is associated with minimizing losses in the electric drive itself, when the frequency of the voltage on the stator is controlled by adjusting the speed of the electric drive at specified slip values in an induction motor, and the impact on the magnetic flux of the motor due to the change in voltage on the stator minimizes steel losses [27]. This method is in order of magnitude more effective than the first two [28] and, naturally, it should be preferred.

The methods for calculating electric power consumption by electric drives with different ways of controlling the air flow in the gas-air path of boilers, the results of experimental measurements, passport data and characteristics of units allow us to proceed directly to the choice of the most advantageous version of the BMM adjustable electric drive and predict the amount of possible energy savings formulated in [29].

You can offer the following sequence of calculations. For a given boiler capacity, on the basis of the regime map, determine the required gas flow rate Q_{G} and according to it the air flow rate Q_{AIR}. Using the aerodynamic characteristic of BMM, one proceeds to the determination of the magnitude of the pressure H and the efficiency of the aggregate η_{BMM}. When throttle flow control should use the main characteristic, when $\theta_{\mathrm{GD}} = 0$, while controlling the flow rate guide device - particular, when this angle is different from zero. With low energy costs, there is practically no difference between these methods. With the maximum performance of the boiler, when the flow rate is $Q \approx Q_{\mathrm{MAX}}$, this difference, as shown by calculations for BMM electric drives, can reach up to (10–15) % in favor of controlling the flow rate by the guide vanes.

In the case of flow control by changing the angular velocity of the BMM shaft (for example, with frequency control), the aerodynamic state of BMM at point G should be taken as the starting point [30]. Since at a fixed position of the blades of the guide vane the flow rate is proportional to the angular velocity of the shaft BMM, to obtain an air flow equal to Q, the angular velocity of the aggregate must be reduced to the value: $n = n_0 \cdot Q / Q_{\mathrm{EXT}},$ where n_0 is the angular velocity of the shaft of the unit, for which its main aerodynamic characteristic is given (usually the nominal speed of the drive induction motor when operating from an industrial network of 50 Hz); Q - the current value of the flow. Usually $Q_{\mathrm{MIN}} \leq Q \leq Q_{\mathrm{MAX}}$; Q_{MIN} and Q_{MAX} are the flow rates at the minimum and maximum heat output of the boiler; Q_{EXT} is the maximum possible for this unit, the flow rate created by the BMM at the maximum (usually nominal) angular velocity of the unit and fully open regulating devices (gates, guide vanes) installed along the gas-air path.

The magnitude of the pressure drop created by the BMM is proportional to the square of its angular velocity [31], therefore: $H = H_G \cdot (n / n_0)^2$, where H_G is the pressure drop corresponding to the point G in [32], i.e. generated by the BMM at the maximum speed of the unit n_0 and fully open control devices.

Mechanical shaft power BMM is determined based on the expression $P_{SHAFT} = H \cdot Q / \eta_{BMM}$.

Finally, the electric power consumed by the electric drive from the network $P_{NET} = P_{ACT} = P_{SHAFT} / \eta_E$.

For air flow values in the range: $Q_{MIN} = 1.52$ m^3/s $< Q < Q_{MAX} = 4.0$ m^3/s.

Using the curves [33], the values of electric power consumed from the network by the electric drives of the fan and the exhaust fan are calculated for each of the considered methods of controlling the flow: using a throttle, guide vanes or changing the angular velocity of the BMM shaft.

The calculation results are shown in [34]. This indicates: P_{ELTR}, P_{ELGV}, P_{ELVR}, - the power consumed by the BMM electric drive from the network, with throttle regulation, regulation by guide vanes and regulation by changing the angular velocity of the BMM shaft.

Total annual electricity consumption of all BMM electric drives: $W_{YEAR} = \sum P_{ELJ} \cdot \Delta t_J$, where P_{ELJ} is the electric power consumption by BMM electric drives (by the fan and the smoke exhauster), when the flow is equal to Q; Δt_J - the duration of the BMM with the value of the flow Q.

when regulating the flow guide devices: $W_{GD} \approx 105000$ kW · h, and finally, when controlling the flow rate by changing the angular velocity of the shaft BMM (frequency control): $W_{VR} \approx 10{,}000$ kW h.

Such a significant (about 110,000 kW · h / year) difference in power consumption when switching to frequency regulation of the shaft speed BMM of the boiler DE-16-14 should be explained by the large head margin that fans and smoke exhausters installed on the boiler have.

Comparing the values of electric power consumption by BMM electric drives with various methods of air flow control, we obtain the following calculated values of annual energy saving:
in electric drives of BMM of the boiler DE-16-14 in the transition from throttle control of air flow to the frequency $\Delta W_{TR} \approx 110000$ kW · h / year; electric drives of BMM boiler PTVM-30M: $\Delta W_{PTVM} \approx 70000$ kW · h / year; electric drives of BMM boiler KVGM: $\Delta W_{KVGM} \approx 86000$ kW · h / year.

5. Suggestions and results of implementation

The proposed methods for improving energy efficiency can and should be used at different stages of the design and implementation of electromechatronic systems. Thus, the improvement of the elemental base can significantly reduce the energy consumption in the power channel of the electromechatronic system and at the same time perform a quantitative assessment of such a solution and the period of its economic payback. The choice of the optimal management structure is necessary at the stage of adjustment and system setup. The proposed computational mathematical model that allows to perform the calculation of energy efficiency is successfully used at the metallurgical production facilities of the Ural region at the stages of calculating and justifying mechatronic systems.

6. Conclusions

In this paper, it was proposed to compare energy efficient solutions of different types of electromechanical transducers, a method for calculating specific mass and mass parameters of electrical machines as elements of mechatronic systems was proposed. It is shown that due to the transition to new types of electromechanical transducers and with an appropriate choice of control laws, it is possible to reduce energy consumption by about 1.5 times. This is achieved through more efficient electromechanical energy conversion in mechatronic systems

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