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Power optimizing control of grinding process in electromagnetic mill

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Abstract— **The paper presents optimizing control of the electromagnetic grinding system. The electromagnetic grinding is a complex process, thus formulation of the optimization problem is done in a top-down manner. To do so, the parameters which influence product quality and serves as decision variables are specially selected. The selection follows from environmental analysis of the system and discussion of the dynamics of disturbances which affect the grinding process. The criterion function to be minimized is electrical energy consumption. Algorithms solving optimization problem are described in the paper. The optimizing control performs as adaptive-like system where minimum energy is kept by proper control of the inverter. Control system constitutes an element of SCADA layered structure.**

Keywords—electromagnetic mill, grinding process, hierarchical control, process optimization.

I. INTRODUCTION

Comminution of the raw material is a well known and widely used operation in mineral processing, construction, chemical, food or pharmaceutical industry. While required parameters of the comminution products can differ significantly (i.e. particles size or shape), a certain problem stands common, namely energetic efficiency of the process. In many cases crushing or milling is one of the most energy consuming part of the technological line [1]. The most popular solutions use ball mills, rod mills, autogenous grinding or semi-autogenous grinding mills. Most of the energy is consumed to rotate the grinding medium and the mill shell. A novel idea is the electromagnetic mill where ferromagnetic grinding media rotate in the inducted electromagnetic field [2]. There are no other moving parts so the energy is consumed only by the electromagnetic phenomena. However, to perform effective grinding the proper loading and classification circuit need to be designed and number of grinding parameters must be controlled.

The paper presents a novel idea of the electromagnetic mill in dedicated grinding and classification circuit with pneumatic transport (section II). All results have been obtained by real-world experiments. Different aspects of the optimization problem are discussed in section III. In this paper formulation based on inverter frequencies and grinding media volume is presented. Solution of the optimization problem is derived in section IV while section V concludes the research results.

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II. ELECTROMAGNETIC GRINDING

Grinding in the electromagnetic mill is performed by the ferromagnetic grinding media (small rods) which move in rotating electromagnetic field. The EM inductor is supplied by the inverter thus precise control of the filed frequency is possible. The raw material is transported pneumatically [3] through the working chamber where collisions between the rods and the processed material cause the grinding effect. The idea of the circuit is presented in Fig. 1. Elements of the installation are presented in Fig. 2. Vertical position of the working chamber gives rise to the counter-flow of pneumatic transport and the fresh processed material stream. The feed is loaded from the top by the auger conveyor, and the transport air is supplied from the bottom of the chamber. Particles of desired size move upwards with the air stream and they are collected at the top end (the outlet) of the working chamber. Depending on the initial size of the particles and the material hardness, the required comminution time is different and determines the mill throughput. Oversized particles leave the working chamber prematurely and return with the stream of the fresh feed. To control the cut-off size precisely, the main classifier (inertial separator) is built in the circuit [4]. The separation is controlled by the air speed throughout the classifier. Thus, the additional air stream is supplied at its input. The final product (fine particles) leaves the separator as an overflow stream and it is separated from the transporting air stream in a cyclone. Coarse particles are fed back pneumatically to the working chamber through the bottom of the mill for regrinding (recycle).

The dry grinding process generates significant amount of heat thus it is equipped with the cooling system using set of electrically controlled fans. Together with a feed humidifying system it allows to control product temperature and humidity.

Low-level control of the electromagnetic mill is a challenging task. Vertical arrangement of the working chamber and counter-flow transport of the material need precise control of the air flow through the working chamber. Otherwise the processed material may fall to the bottom of the mill or may be sucked out of the mill without grinding. To reach required quality of grinding, the proper fulfilment of the working chamber must be kept. The fulfilment level depends on actual throughput of the mill, fresh feed and recycle ratio, volume of the grinding media and on transport air streams ratio. On the other hand the classification process in the inertial separator requires precise control of the transporting air flow which is composed with the air leaving working chamber and the additional air stream at the separator input. Thus control of the fulfillment disturbs the separation process. Another task of the control system is to stabilize the ratio of the raw material to the grinding media volume in the working chamber according to the EM field frequency. Experiments showed a big impact of these parameters on the grinding process quality. The effectiveness of grinding depends also on temperature and humidity of the raw material. All of the parameters mentioned above are mutually dependent. The parameters are changing or need to be controlled with different rates. Such complexity requires application of hierarchical control system [5]. The general idea of such control is depicted in Fig. 3.

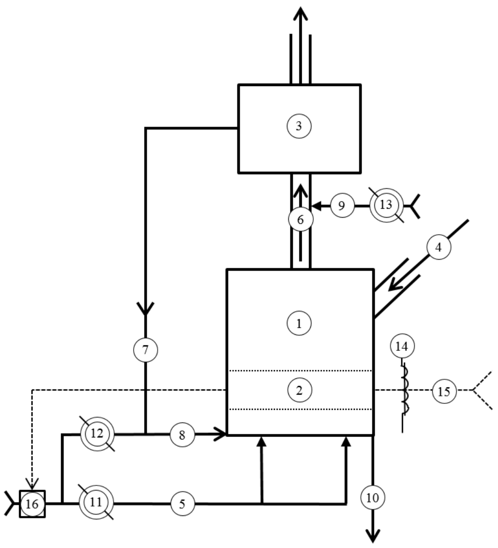

Fig. 1. Grinding and classification circuit diagram, where 1: electromagnetic mill, 2: working chamber, 3: inertial separator, 4: fresh feed stream, 5,: main transport air stream, 6: mill product output, 7: coarse particles stream, 8: recycle stream, 9: additional transport air stream, 10: oversized particles stream, 11-13: air flaps, 14: electromagnetic filed inductor, 15: cooling air stream, 16: heat exchange unit.

On can distinguish four control layers: direct control, supervisory control, optimization and production management. The main task for every layer is to attenuate different disturbances influencing the plant. The fastest disturbances are regulated by the direct control (fulfilment of the working chamber, raw material humidity and temperature, speed of air streams etc.), while the slowest are the task for the production management (e.g. type of the material to be processed).

One can also distinguish different subsystems in the plant with regard to the process characteristics. For every subsystem the direct control structure was described and parameterized. Some of the main tasks of the direct control are as follows: working chamber air flow stabilization, inertial separator air flow stabilization, grinding media volume control, working chamber fulfillment control, raw material humidity control, product temperature and humidity stabilization. An important problem, not presented in this paper is measurement system.

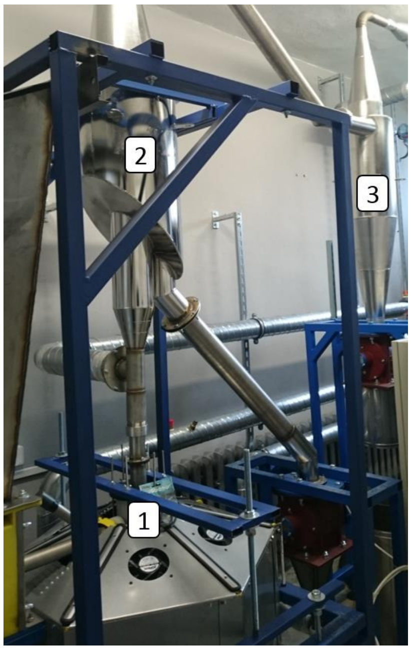

Fig. 2. Grinding and classification circuit in the Silesian University of Technology: 1 – electromagnetic mill, 2 – inertial separator, 3 – cyclone.

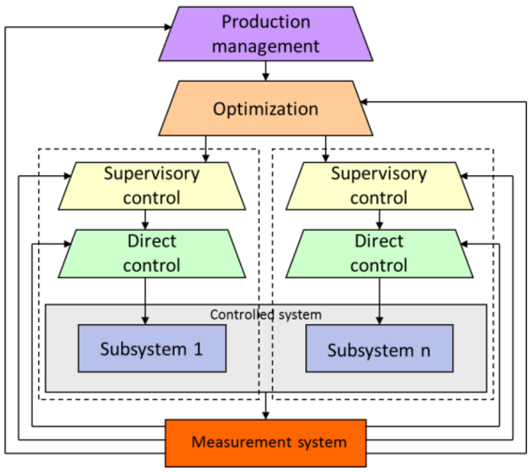

Fig. 3. General structure of the hierarchical control system

Supervisory control focuses mainly on the set-points correction for the particular control loops, taking into account all cross-couplings. It is also aimed to parameterize inverter output and basic frequencies, grinding medium parameters, feed humidity and heat recovery system parameters. This is discussed more precisely in the following section of the paper.

III. OPTIMIZATION PROBLEM

There are two major optimization issues in the electromagnetic grinding systems. The first is maximization of the production and the second concerns minimization of the energy consumption. Demands of technological environment of the electromagnetic grinding system determinate the way in which the optimization problems are formulated. The rate of production is optimized in the highest layer shown in Fig. 3. This is management level rather than the control level. Formulation of the production optimization problem refers to the planning aspects which are mostly focused on the market and economic analyses and concern warehouse management, plant maintenance, sales management etc. Disturbances affecting this (management) layer are relatively slowest in the production system. Lower layer (optimization – see Fig. 3) responds to faster disturbances like feed parameters or air stream parameters changes. Large difference between horizons in which the decisions are undertaken in management layer and optimization layer makes possible division of the optimization problem into the two mentioned layers.

In this paper only optimization layer is discussed. It is assumed that the production (feed) is constant and determined by the upper (management) layer. The production value can change but the layered hierarchy makes the production so called *leading variable* for the optimization which means that optimization layer assumes constant and given production rate. The aim of the optimization layer is then minimizing energy consumption for the given production with respect to the production quality. The grinding quality can be described by granulation. There are three material streams in the system where granulation needs description (measuring or modelling): feed ($\mathbf{p}_f$), recycle ($\mathbf{p}_r$) and final product ($\mathbf{p}_p$). Theoretically granulation is represented by a continuous function of average percentage content or weight content of grains in the stream expressed as distribution or cumulative content. Fig. 4 presents example of cumulative grain content of copper ore being grinded in electromagnetic mill. Feed contains only large class, practically of the size 1-1.4 [mm] (particles of the size lower than 1 [mm] are less than 20% in the feed). It can be noticed that electromagnetic mill grinds mostly to the low sizes (class less than 0.1 [mm]) leaving the rest of the output greater than 1 [mm]. The results shown in Fig. 4 have been obtained in a feedforward case i.e. no recycle has been applied. After eventual classification, part of the output stream can be returned back into the mill and contribution of the larger class in the product is reduced.

A model of the grain distribution is needed for the optimization. Literature delivers a lot of types of the models. Basis of the modelling has been developed by Epstein [6] and Kołomogorow [7] who proved that under certain assumption the grain distribution is logarithmic-normal function. Survey of the grain distribution (partition) modelling and simulation can be found in [8]. In practice, however, granulation is measured in chosen points of the partition curve (obtained by e.g. sieve analysis), thus the vector $\mathbf{p}_f$ ($\mathbf{p}_p$ or $\mathbf{p}_r$) contains certain values of the partition function. Although direct imaging and laser diffraction methods provide multipoint results, still the most commonly used are metrics given in a few characteristic points. For example when describing particle size distributions, so-called *d*-values (e.g. d_{10}, d_{50} and d_{90}) which are the intercepts for 10%, 50% and 90% of the cumulative mass [9]. Thus exemplary metrics of partition for the feed case presented in Fig. 4 are as follows:

$$\mathbf{p}_f = \begin{bmatrix} d_{10} \\ d_{50} \\ d_{90} \end{bmatrix} = \begin{bmatrix} 0.7 \\ 1.18 \\ 1.33 \end{bmatrix}, \quad \mathbf{p}_p\Big|_{F_f=0.154[Mg/h]} = \begin{bmatrix} 0.02 \\ 0.88 \\ 1.31 \end{bmatrix}, \tag{1}$$

Other quantities characterizing partition can be derived from d-values as e.g. probably dispersal or imperfection [9] which are very useful in evaluation the partitioning. In the grinding processes, however, more suitable is simple collection of chosen values of cumulative granulation function. Number N of chosen grain sizes and their values (arguments of the function) follow from technological demands. In the case presented in Fig. 4 collection of the arguments (expressed in [mm]) are as follows (N=6):

$$\mathbf{d} = \left[0.1, 0.2, 0.4, 0.63, 1, 1.4\right]^T . \tag{2}$$

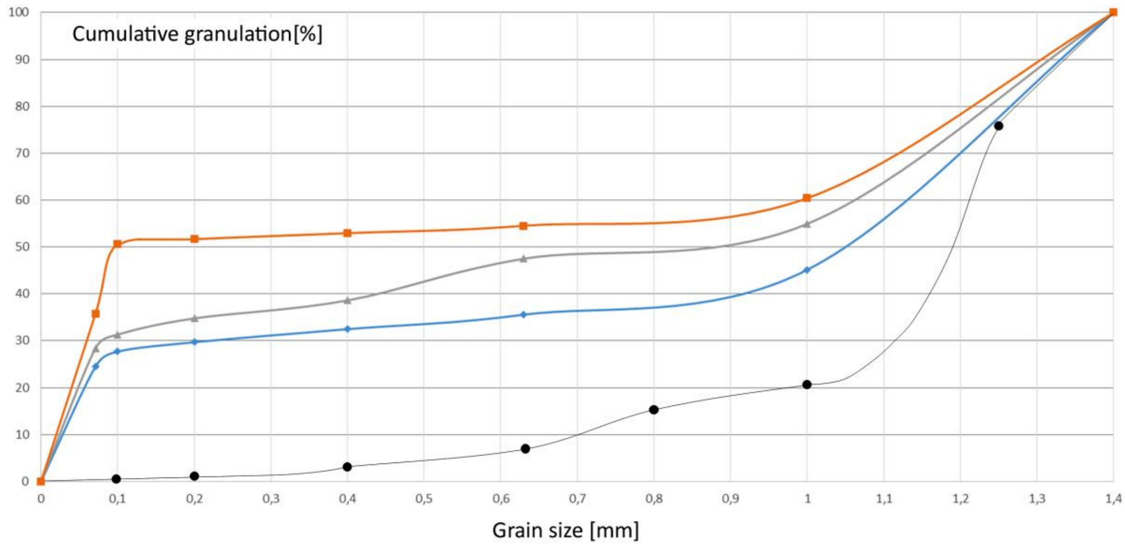

Fig. 4 Cumulative granulation of copper ore (black line– feed, blue line – product obtained for the feed volumetric flow F_f=0.307 [Mg/h], grey line – product with F_f=0.154 [Mg/h] and orange line – product with F_f=0.077 [Mg/h]).

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The following results of sieve analysis (expressed in [%]) of the product and feed have been obtained

$$\begin{aligned} \mathbf{p}_p\big|_{F_f=0.307[Mg/h]} &= \left[27.69, 29.70, 32.49, 35.58, 45.15, 100\right]^T , \\ \mathbf{p}_p\big|_{F_f=0.154[Mg/h]} &= \left[31.31, 34.78, 38.61, 47.51, 54.94, 100\right]^T , \\ \mathbf{p}_p\big|_{F_f=0.077[Mg/h]} &= \left[50.65, 51.67, 52.96, 54.54, 60.42, 100\right]^T , \\ \mathbf{p}_f &= \left[0.04, 0.98, 3.18, 8.29, 20.72, 100\right]^T , \end{aligned} \tag{3}$$

where E_f is the feed volumetric flow. Vector $\mathbf{p}_p$ depends not only on E_f but also on number of parameters of the whole electromagnetic grinding system. Generally, one can expect the following relation (vector field):

$$\mathbf{p}_p = \mathbf{p}_p\left(\mathbf{\Omega}, \mathbf{F}, \mathbf{A}, \mathbf{R}, \mathbf{M}\right) \tag{4}$$

where:

- vector $\mathbf{\Omega}$ contains inverter frequencies (output frequency ω_o and basic frequency ω_b)

$$\mathbf{\Omega} = \left[\omega_o, \omega_b\right]^T , \tag{5}$$

- vector $\mathbf{F}$ contains parameters of the feed:

$$\mathbf{F} = \left[F_f, d_f, h_f, T_f, \mathbf{p}_f^T\right]^T , \tag{6}$$

  with: F_f – feed volumetric flow, d_f – density of the feed, h_f – humidity of the feed, T_f – temperature of the feed, $\mathbf{p}_f$ – granulation parameters of the feed (explained above),
- vector $\mathbf{A}$ contains parameters of the air volumetric flow through the grinding chamber:

$$\mathbf{A} = \left[F_a, T_a, h_a\right]^T , \tag{7}$$

  with: F_a – total air volumetric flow through the grinding chamber (controlled by a specially designed algorithm realized in supervisory layer [14]), T_a – temperature of the air flow F_a, h_a – humidity of the air flow F_a,
- vector $\mathbf{R}$ contains parameters of the recycle flow:

$$\mathbf{R} = \left[F_{ar}, F_{mr}, \mathbf{p}_r^T\right]^T , \tag{8}$$

  with: F_{ar} – recycle air volumetric flow, F_{mr} – recycle grinded material mass flow, $\mathbf{p}_r$ – granulation parameters of the recycle flow, which follows form the classifier parameters and corresponds to $\mathbf{p}_f$ explained above),
- vector $\mathbf{M}$ containing parameters of the grinding medium:

$$\mathbf{M} = \left[m, \mathbf{p}_m^T\right]^T , \tag{9}$$

  with: m– mass of the grinding medium, $\mathbf{p}_m$ – parameters of the grinding medium (size, type of the ferromagnetic material etc.).

Parameters (or variables) gathered in (4) influence $\mathbf{p}_p$ in a different way and play different role in the electromagnetic grinding system. Inverter frequencies ω_o and ω_b determine speed of grinding and are set by supervisory control layer. The feed flow F_f is established by management layer as discussed above. Physical parameters of the feed (d_f, T_f and $\mathbf{p}_f$) are determined by preceding and preparing units. The exception is feed humidity h_f which is partially controlled by direct control layer (increasing by adding water spray to the feed stream to improve efficiency of grinding [13]) and partially controlled by the supervisory layer which sets air stream $\boldsymbol{F_a}$ which can dry the feed in a proper way. Humidity h_a and temperature h_a of the air stream are controlled by the additional system of heat recovery. Electromagnets of the mill heat up and need cooling by fans. Hot air stream from the fans are collected and directed to the main air intake where mixes in the controlled way (heat exchange unit labeled by '16' in Fig. 1).

Recycle has a big impact on the product quality. However, in this work only feedforward case (so called open structure) is discussed. We recapitulate the recycle (so called closed structure) in the conclusion which refers to the further work. It is then assumed F_{ar}+F_{mr} = 0.

Parameters of the grinding medium influence the product quality as well. Mass of the medium decreases due to devouring. Respective supervisory layered algorithm controls the mass and adds a proper portion.

Relation (4) serves for development of the constrains for optimization problem formulation. The product quality can be judged in a different way according to technological requirements. Most commonly low class of granulation is desirable. A simple way to express quality demand is to introduce boundaries for $\mathbf{p}_p$ as follows:

$$\mathbf{p}_p^l \le \mathbf{p}_p \le \mathbf{p}_p^h \tag{10}$$

It follows form the above discussion that different variables determine quality of the production. Part of them are independent variables which are treated as given parameters (e.g. d_f, T_f and $\mathbf{p}_f$). Rest of the variables are decision variables of the optimization problem. In this work only inverter frequencies ω_o and ω_b constitutes decision variables.

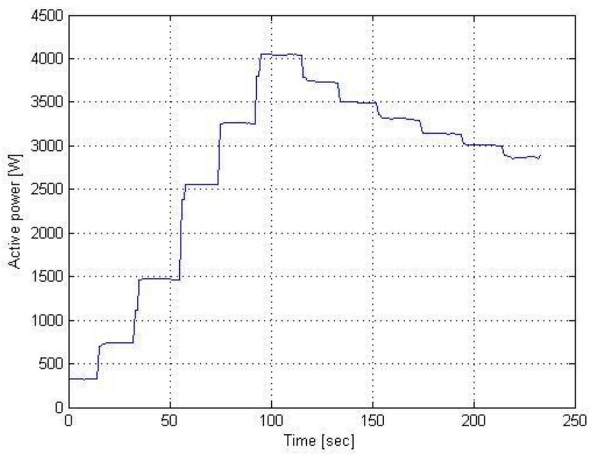

Fig. 5 Active power generated by the inverter for different output frequency.

In the electromagnetic grinding systems, the electrical energy is consumed by different units but only one is controlled i.e. drive of the electromagnetic mill. As mentioned in sec. I, ferromagnetic particles move around the milling chamber being activated by electromagnetic field which rotates with frequency ω_o. Frequency ω_o is set by the control system in the inverter (so called output frequency). The second parameter of the inverter being set by the control system is basic frequency ω_b. The cost function J of the optimization task can be then expressed as follows:

$$J = J(\omega_o, \omega_b) \tag{11}$$

It is useful to take, instead of energy consumption, an average active power, generated by the inverter and calculated in assumed period of time. Several experiments using the electromagnetic grinding system have been conducted to evaluate relation (11). Fig. 5 presents results of an exemplary experiment. Active power has been registered with sampling time 1 [sec]. The basic frequency was kept constant (50 [Hz] in experiment presented in Fig. 5), and the output frequency was changed in a step wise every 20[sec] (the sequence: 10, 20, 30, 40, 45, 50, 55, 60, 65, 70, 75 and 80 [Hz]). Active power has been averaged in every subinterval by taking steady state measurements (it can be seen from Fig. 5, that steady state is reached in 3-4 [sec]). Dynamics of the response follows form mechanical inertia of the electromagnetic mill chamber filled with ferromagnetic particles. After series of such experiments, the relation (11) has been obtained. Fig. 6 presents the results, plotted directly from the obtained data and smoothed using simple spline interpolation. In these experiments basic frequency has been set around 50 [Hz] i.e. from 40 up to 60 [Hz]. Great changes of the active power with respect to output and basic frequencies can be seen in Fig. 6. Both frequencies influence the active power the most.

Experiments were repeated for different (independent) variables, i.e. arguments of the relation (4) as well. Shape and position of the surface change slightly for all independent variables. For example results of the experiment with different mass m of the grinding medium is presented in Fig. 7, shows relation $J(\omega_o, \omega_b = 50, m)$ for the basic frequency equal 50 [Hz] and different mass of the grinding medium. Obviously, active power increases with m.

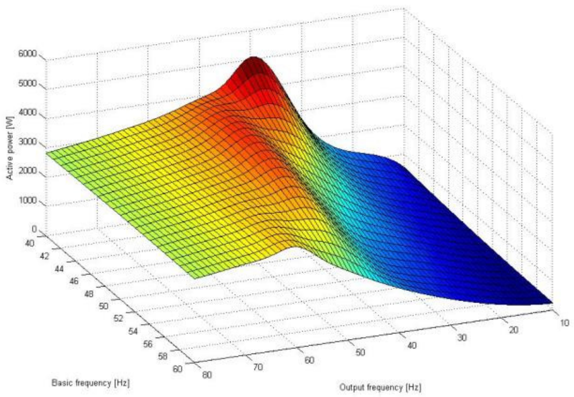

Fig. 6 Active power measured for different output and basic frequencies.

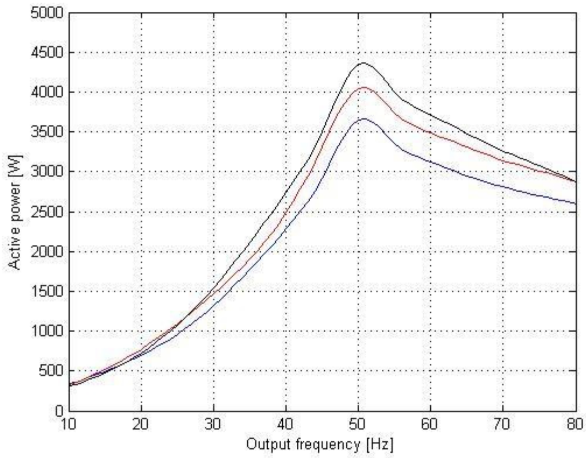

Fig. 7 Active power measured for basic frequency equal 50 [Hz]: black line $m = 600$ [g], red line $m = 400$ [g], blue line $m = 200$ [g],

Results obtained in these experiments justifies the choice of the output and basic frequencies as decision variables of the optimization problem. What is more they created the basis for the algorithm which solves the optimization problem described in the next section. To finish the following optimization problem is formulated:

$$\min_{\omega_o, \omega_b} \; J(\omega_o, \omega_b) \tag{12}$$

with respect to the constrains:

$$\mathbf{\Omega}: \quad \omega_o^l \le \omega_o \le \omega_o^h, \quad \omega_b^l \le \omega_b \le \omega_b^h \tag{13}$$

$$\mathbf{F} = \mathbf{F}_0, \quad \mathbf{A} = \mathbf{A}_0, \quad \mathbf{R} = \mathbf{R}_0, \quad \mathbf{M} = \mathbf{M}_0 \tag{14}$$

$$\mathbf{p}_p^l \le \mathbf{p}_p(\mathbf{\Omega}, \mathbf{F}, \mathbf{A}, \mathbf{R}, \mathbf{M}) \le \mathbf{p}_p^h \tag{15}$$

where $\mathbf{F}_0$, $\mathbf{A}_0$, $\mathbf{R}_0$ and $\mathbf{M}_0$ are values of the independent variables. Values of the independent variables are bounded, but they are not serve as the decision variable thus these boundaries are not taken as the constraints of the optimization problem.

The model (4) is complex, multi-parameterized mathematical relation. Identification of (4) needs numerous experiments, where all independent variables are checked. In [10] generalized polynomial model and its identification is presented. Polynomial structure is very useful for solution of the optimization problem.

IV. Solution of the Optimization Problem

Values of the independent variables are constituted by measurements, by direct control system or manually. It is assumed that all values $\mathbf{F}_0$, $\mathbf{A}_0$, $\mathbf{R}_0$ and $\mathbf{M}_0$ are known. After substitution to (4), the model takes the following form:

$$\mathbf{p}_p(\mathbf{\Omega}, \mathbf{F}_0, \mathbf{A}_0, \mathbf{R}_0, \mathbf{M}_0) = \mathbf{p}_p^0(\mathbf{\Omega}) \tag{15}$$

Model (15) is the set of N two-dimensional generalized polynomial models of the fourth order [10] (entries of the vector $\mathbf{p}_p^0$):

$$\begin{aligned} p_{p,i}^0(\mathbf{\Omega}) = {} & p_i^0 + a_i^1\omega_o + b_i^1\omega_b + a_i^2\omega_o^2 + b_i^2\omega_o\omega_b + c_i^2\omega_b^2 + \\ & + a_i^3\omega_o^3 + b_i^3\omega_o^2\omega_b + c_i^3\omega_o\omega_b^2 + d_i^3\omega_b^3 + \\ & a_i^4\omega_o^4 + b_i^4\omega_o^4\omega_b + c_i^4\omega_o^2\omega_b^2 + d_i^4\omega_o\omega_b^3 + e_i^4\omega_b^4 \end{aligned} \tag{15}$$

where i = 1,2,…, N corresponds to the chosen grain sizes. Finally constrains of the optimization problem for the given $\mathbf{F}_0$, $\mathbf{A}_0$, $\mathbf{R}_0$ and $\mathbf{M}_0$ can be expressed according to (10) as follows:

$$p^l_{p,i} \le p^0_{p,i} \le p^h_{p,i} \tag{16}$$

where $p^l_{p,i}$ and $p^h_{p,i}$ are entries of the vectors $\mathbf{p}^l_p$ and $\mathbf{p}^h_p$ respectively. It is now clear, that the solution of the optimization problem for given $\mathbf{F}_0$, $\mathbf{A}_0$, $\mathbf{R}_0$ and $\mathbf{M}_0$ is reduced to (12) subject to (13) and (16).

It must be admitted, that independent variables change much slower than output and basic frequencies. It follows from the frequency range of disturbances which activate upper (management) layer or cause operational points of the electromagnetic grinding system (e.g by changing set points of the respective controllers of direct control layer or by manual resetting of the load parameters). This opportunity makes possible to apply the following two-step algorithm of the optimization problem solution:

1. Find the range of frequencies ω_o and ω_b which fulfills (16) with respect to (13):

$$\omega_o \in [\underline{\omega}_o, \bar{\omega}_o], \qquad \omega_b \in [\underline{\omega}_b, \bar{\omega}_b], \tag{17}$$

2. For the given ranges find minimum (12).

The first step is solved using relaxation method [6]. Algorithm starts with initial ranges given by (13). Obviously it rarely happens that these range fulfil (16). Thus the range needs contraction which is done iteratively. First step in the iteration is to find ith constrain (16) i=1,2, N for which exceeding the limits is greatest. Then contract bounds to reach limits in this constrain only. Apply new range to other constraints and repeat calculations, until every constrains (16) are fulfilled.

The second step of the algorithm performs in the control system on-line. Algorithm is realized in the SCADA system. In every 5 [sec] new pair (ω_o, ω_b) is set and the instant active power is measured. Minimization (12) is done by comparison of the measured power. The algorithm bases on Powell directional maximization [12].

V. Conclusion

Optimization of the electromagnetic grinding system refers to number of parameters which influences product quality. The paper describes these parameters and formulates optimization problem by extraction decision variables from the set of parameters leaving the rest as independent variables. Such an extraction follows from environmental analysis of the system together with the discussion of the dynamic of the disturbances which affects grinding process. Yet another important issue justifying proposed extraction is layered structure of the control system.

Important characteristic of the presented solution is adaptive-like optimizing control. Indeed, fast sampling which can be applied in active power control by setting output and basic frequency makes possible on-line optimization which continuously searches for the minimum of consumed energy.

Further work is concentrated on heat distribution in the system, especially referred to heat dissipated by electromagnets. This phenomenon is directly connected with electromagnetic induction generated in the working chamber which in turn affects quality of grinding.

Heat recovery serves as the example of the most general direction of the further work namely releasing independent variables to become decision variables in the optimization task formulation. However, this research needs cumbersome and difficult experiments and, presumably no longer simply polynomial model of (4) can be used. Other universal approximators (e.g. fuzzy models) are going to be tested in order to evaluate grinding quality.

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