Regulated Drive of Vibratory Screens with Unbalanced Motors

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Abstract— **Vibratory screens are machines that, when subjected to the mechanical vibration, carry out the separation of material mixtures to granulation, or to fractions. The number of fractions depends on the number of storeys on a vibrating screen. This paper discusses the regulated electric drive of vibratory screens with one storey, used to separate the boiler ash from the slag (bottom ash) in the Thermal Power Plants TENT-B, Obrenovac. Some of the important parameters of vibratory sieving are frequency and amplitude of vibrations, tilt angle of the vibratory screens, and the angle of the actuating force acts on the vibrating screen. The proposed technical solution is provided to adjust all of these parameters. The synchronous operation of vibratory exciters is requested, as well as the work of vibratory screens in super-resonant mode. The paper presents the experimental results and determining the amplitude-frequency (AF) characteristics of the vibrating screens.**

Keywords: Vibratory screens, slag (bottom ash), fly ash, vibration control, unbalanced motors, power drive, IGBT, frequency converter

I. Introduction

Vibratory screens (vibratory sieves) are machines commonly used in many applications in the industry for process separation of the mixture of materials to the granulation, or the fraction. The number of fractions depends on the number of storeys to the machine construction. Vibratory screens (VS's) can be used for dry sieving or screening in addition to rinsing system [1], [2], [3-4]. In addition to the effect of sieving, the conveying of separated material along the oscillating inclined grid surface is very important. In these cases, the acceleration and deceleration of VS's is critical, considering that the impact of its short passage through the resonant frequency becomes significant when the stress of the whole mechanical construction is considerable. [5].

The excitation of VS's can be accomplished in a circular or elliptical oscillation. The detailed dynamic analysis and obtaining of the dynamic characteristics of large VS are given in detail in the references [6-10]. The unbalanced circular VS's are made with the central axis of the frame (usually in the centre of gravity) which is not linked to the supporting structure of VS's. The self-adjustable unbalanced masses are mounted on the shaft. The frame of VS is elastically supported at the ends using the elastic springs to the supporting structure. Therefore, the circular vibrations, which have approximately the same restoring forces, act in all directions. Hence, in this case, the relatively "soft" springs (stiffness is very small) are being used, so that the VS frame and unbalanced masses are rotating together around a common centre of gravity [11]. The efficient processes of separation and sieving of materials are obtained by VS's that perform elliptical oscillations in two or three axis. The dynamic and structural analysis of these large VS is given in detail in key references [12-15] in this field.

For the operation of VS's, four parameters are significant: amplitude and frequency of oscillation, the mass of the mixture that is sieved mass, VS tilt angle to the horizontal, and the angle of incidence of the excitation force acting on the grid of sieve [1-3].

The changing oscillation amplitude of VS troughs affects the intensity of sieving. It is usual that this change is done by mutual (relative) turning of eccentric flywheels. The standard three-phase squirrel-cage asynchronous motors are used as drive actuators. The changing frequency of oscillation affects the quality of sieving, and it is realized directly by changing the rotary speed of the drive motors. The increase in mass in the VS trough requires increasing the power or the forces i.e. torque of the drive motors [5].

The VS's are often applied to the thermal power stations in coal cleaning systems [16], but they are also used in systems for transporting of slag and separation of ash from the slag. This paper presents an improved technical solution for two independent regulated VS electric drives, each with one storey, used in the system for the slag transport and fly ash separation (which comes from electrostatic precipitator station), in Thermal Power Plant TENT-B in Obrenovac, Serbia. The sieved ash particles are drained further, through an appropriate transport system, into a collecting pipeline. The separated larger chunks of slag (approximate mean diameter of 30 mm-80mm) are transported to the crusher, where their further processing and grinding is performed. After this, the grind slag is also transported into the collection pipeline, where it is mixed with sieved ash particles. After this, the new mixture is transported via water ejector to landfill. The numerous problems in the operation of VS's, as well as the critical electrical and mechanical parts of the system, have imposed a series of technical interventions in order to improve the vibratory separation slag (bottom ash) from the boiler ash.

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II. THE PROBLEMS IN THE OPERATION OF PREVIOUS SYSTEM

The old system of sieving consisted of two independent VS's. The basic mechanical structure of each of the VS's consisted of a vibratory trough leaning on a supporting frame via steel helical springs. Due to the large lateral and longitudinal shock stresses, fatigue occurred, and, subsequently, the cracking and damaging of the helical springs. The excitation system caused mechanical oscillations of VS's on elliptical trajectory. The excitation force was caused by the rotation of eccentric flywheels mounted on the upper part of the VS trough. Eccentric flywheels were placed on a common shaft. The drive was achieved by an asynchronous motor with belt transmission. Layout of this system is shown in Fig.1.

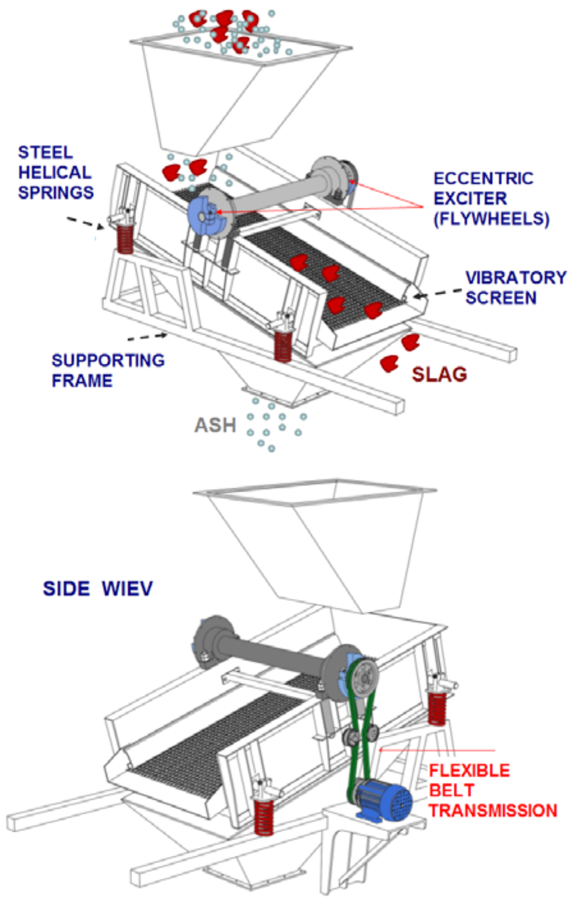

Figure 1. The drive of old system of vibratory screens on thermal power plant TENT-B

Rated rotation speed of asynchronous motor was 1450 rev/min (synchronous speed of 1500 rev/min, the number of pole pairs $p = 2$). The drive was unregulated, with a direct starting of electric motors with no possibility of speed change or the oscillatory frequency of VS's. The belt transmission drive was based on spring pretensioners. Due to increased shock oscillations, the belts in the transmission system would often crack. Due to the motion of the centre of gravity of VS in elliptic trajectory and its oscillatory movement, the effect of transporting the separated slag along the VS grid was weaker. This led to a prolonged retention of slag on the grid sieves, and even its return upwards, instead of being transported down to the entrance to the hopper of crusher. As a result of these problems, the slag and ash transport would often come to a standstill, which prevented the normal operation of the transportation system, and, in the worst case, the normal operation of the corresponding block of thermal power plant. Also, during normal operation (during the correct operation of the transmission system and when the supporting steel helical springs is in function) there was the congestion of slag and ash transport, since the entire drive was uncontrollable regarding both amplitude and frequency). For the above-mentioned reasons, the existing VS's were completely reconstructed. The reconstruction consisted of the design, dismantling of the existing system and installation of a new, reliable, and adjustable system, as well as the commissioning and final exploitation, as part of an integrated slag and ash transport system.

The essence of a new, improved technical system of regulated drives of VS's will be described below.

III. THE DESCRIPTION OF RECONSTRUCTED DRIVES OF VIBARTORY SCREENS

Within this technical solution for both vibrating sieves, the designing of the following was done: unbalanced exciter (mechanical and electrical calculations), exciter bracket (mechanical calculation), supporting elastic composite elements of VS (mechanical calculation), electrical control units of exciter system, including the control of vibratory frequency (electrical calculation), exciter system with adjustable amplitude of excitation force, system of adjusting the tilt angle excitation force and the system of continuous electronic regulation of the oscillation frequency (2 Hz-120Hz). A frequency regulation is necessary in order to achieve the optimal vibratory transport and screening, for various regimes and various types of granulation of materials.

Before the development of the system, all the technical calculations were verified by numerical finite element methods, in addition to the simulations of elastic stresses in the composite elements, analysis of deformation under specified load cases, the fatigue study etc.

Fig.2 shows the final technical solution for VS drives. The essence of this solution is, in fact, replacing the belt transmission eccentric drive with unbalanced motors as exciters. These exciters include an integrated flywheel unbalanced mass and they are regulated by an electric drive, shown in Fig.2 (a). The vibratory exciters are separately built in and there is no direct mechanical coupling. The drive of flywheel masses in each exciter was performed with a standard three-phase asynchronous motors, power of 2.2 kW, nominal rotation speed of 1500 rev / min, with two pairs of poles ($2p = 4$). In addition, there was a replacement of steel helical springs. Considering that these springs are substantially loaded transversely and longitudinally, the idea was to replace the steel springs with elastic composite elements. These elements are very well tolerated by both static and dynamic stresses, but they also quickly soothe the increased amplitude of oscillation. A significant improvement of VS was performed by implementation of the swivel mechanism in the system vibratory exciter, by which an optimal angle between the direction of exciting force and the plane of grid sieve is determined. The swivel mechanism is shown in Fig.2 (b). It consists of several crucial parts: sliding plate, stationary plate, clamping plate and bearing plate.

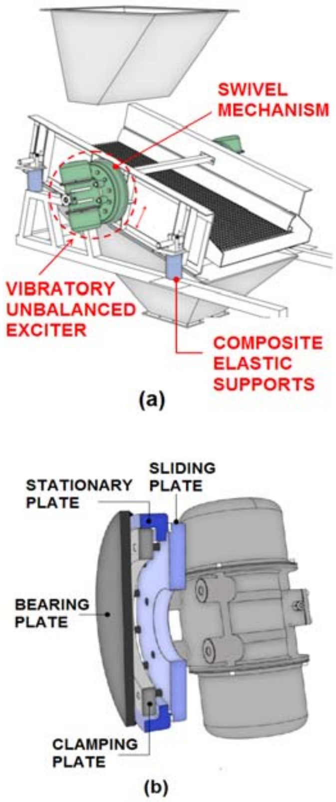

Figure 2. The final solution of vibratory screen with unbalanced motors; (a) layout of entire system, (b) swivel mechanism in unbalanced exciter

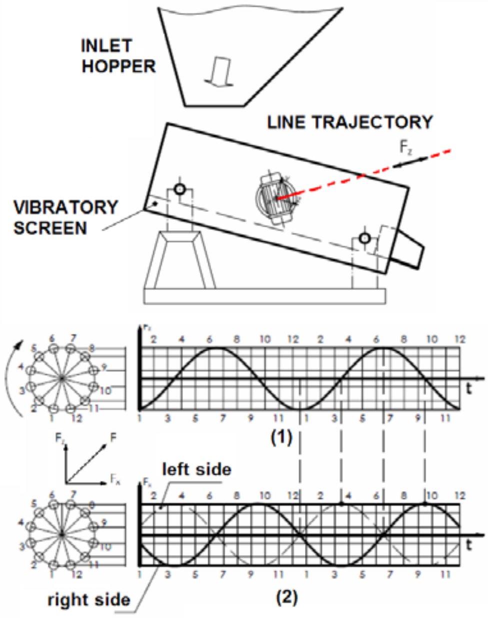

Figure 3. The principle of realisation of linear oscillation of vibratory screen

With the new concept of the vibratory exciter, the linear oscillations of VS were realized. The linear trajectory of VS is shown on Fig.3. The Fig.3 also shows the time diagrams of the force generated by the described unbalance exciter. On the time diagram (1), the excitation force is shown. This force has the sinusoidal character. The time diagram (2) shows the time changes of cancelled equivalent centrifugal force from the exciter on the left and the right side.

The oscillatory actions of exciters are sinusoidal harmonic, but the excitation forces of the left and right are in anti-phase. The vector diagrams of the exciting forces of vibration exciters are given in Fig.4.

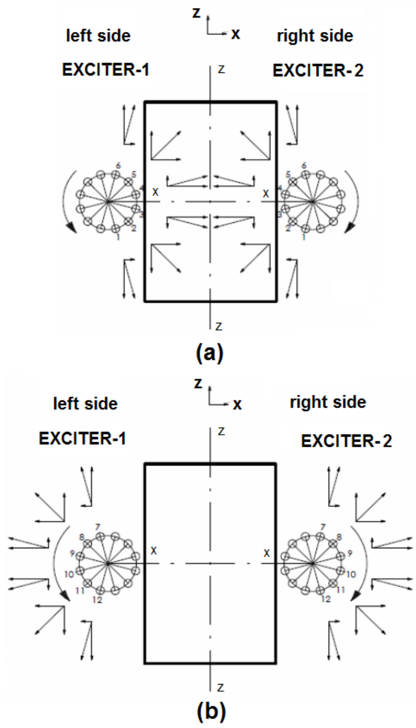

Figure 4. The vector diagrams of excitation forces; (a) force to axis, (b) force from axis

In one case, the excitation force is directed to the axis of VS, shown in Fig.4 (a), while in the second case is directed from the axis of the VS, shown in Fig.5 (b).

The value of amplitude linear oscillating excitation force of VS is achieved by adjusting the swivel angle α [deg] between the eccentric flywheel masses in each of the exciter. The adjustment range of this angle is 0 ° -178 °.

IV. The Regulated Drive of Vibratory Screen

As noted above, and shown in Fig.4, the exciting forces must be synchronized in anti-phase. As a result of any asymmetry, even in ideal mounting of vibration exciter, the linear oscillations may be disturbed and VS's lateral oscillations may appear. To overcome these problems, we introduced an adequate control and measuring of the position and speed of rotation of the eccentric flywheels for both exciters. In order to solve synchronization problems, the authors have developed two alternative solutions.

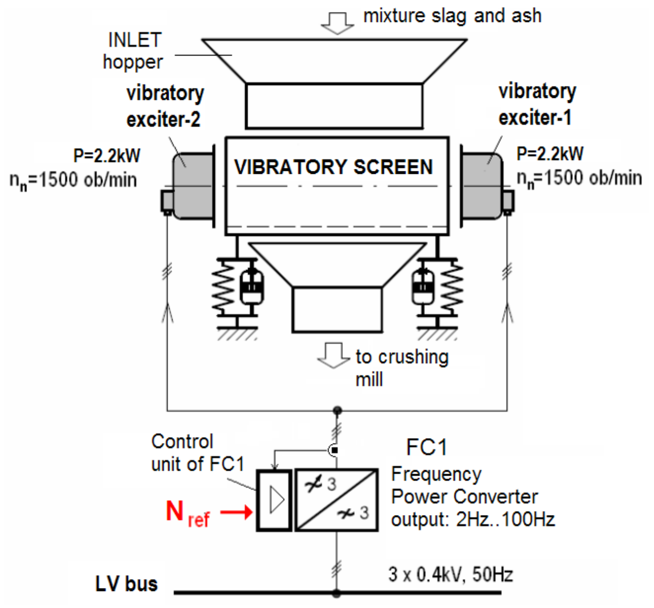

Figure 5. The block scheme of open-loop control (sensor-less) of unbalanced vibratory exciters (unbalanced motors)

In the first variant shown in Fig.5 power drive of unbalanced vibration exciters is realized in the same AC/AC frequency power converter FC1. The power converter combines a sophisticated microprocessor with an advanced IGBT power switching technology to deliver closed loop flux vector and sensor-less vector control of unbalanced drive motors. The proposed solution of control system on Fig.5, is without feedback (sensor-less control), and it implies that there is an ideal mechanical symmetry of the oscillatory mass throughout the entire operating cycle.

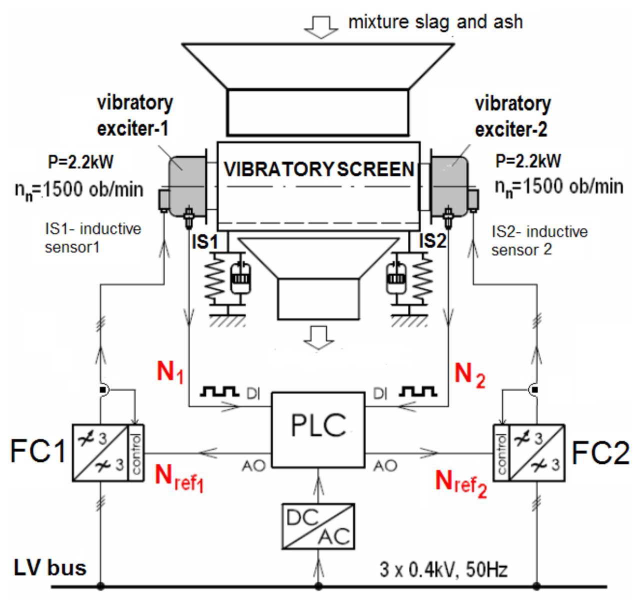

Figure 6. The block scheme of closed -loop control of unbalanced vibratory exciters (unbalanced motors)

A mitigating circumstance is that, due to the effect of gravity on the flywheel masses, the so-called self-synchronization of initial position in the zero state occurs, so that the initial phases of the driving forces are equal. The set point rotary speed (reference) is the same for both drives with unbalanced motors. The IGBT frequency converter provides speed adjustment of unbalanced motors (vibration exciter) i.e. oscillatory frequency of the excitation force in the range of 1Hz-100Hz.

The second variant, shown in Fig.6, powering of each of unbalanced motor is realized with two separate frequency controlled drives, FC1 and FC2. This configuration solves the problem that might arise due to potential de-synchronization of vibratory exciters during the operation cycle.

In this case, the programmable logic controller (PLC) is used as the central control unit, which, based on the signals of the rotation speed N1 and N2 of the each unbalanced motor and based on the implemented algorithm, sets the analogue references N_{ref1} and N_{ref2} of frequency converters FC1 and FC2, respectively. To measure the rotation speed of unbalanced motors, we used very precise, industrial inductive sensors IS1 and IS2, with great immunity to vibration to which they are exposed, since they are mounted on oscillating housing of vibration exciters.

Technical limitations of proposed solution

One limitation would certainly be the mass of slag that unbalanced motors can lead to a state of oscillation and sieving. This mass is determined by the mass of the VS trough and by the slag flow through the inlet feed hopper of the system i.e. m= {500 ÷ 1200}[kg]. Another limitation is the exciting frequency. The limitation of the frequency of oscillation is determined by the mechanical endurance of bearings of unbalanced motors, by the number of poles of its windings, and the characteristics of frequency converters i.e. n= {150 - 3000}[rev/min] or f={5 ÷ 100}[Hz]. The limitation of oscillatory amplitude A_m = {1 ÷ 10} [mm] of VS is determined by the mass and the smallest angle between the eccentric flywheels. The power limit P={1÷4} [kW] is determined by the rated power of electric unbalanced motors. It should be noted that these limitations are interdependent, although they are independently adjusted. Namely, at the maximum power of exciter, it is possible to achieve higher frequency of screening, at low amplitude and vice versa (with the same mass of slag on the vibratory sieve grid).

V. THE EXPERIMENTAL RESULTS

After the reconstruction of the VS's drive, it was necessary to perform measuring, testing and verification of their technical characteristics. The reconstructed drives provide adjust frequency and amplitude of the resulting excitation force. Also, with developed mechanism for the slewing of the flywheel masses in vibration exciters, it is possible to adjust the angle β between the direction of the resulting linear excitation force and the plate of VS grid (lattice). The grid (lattice) of VS is inclined relative to the horizontal plane under constant (unchangeable) angle of 15°, so that the angle between the direction of excitation force and the horizontal grid (lattice) is $\varphi = \beta + 15°$. During the exploitation tests on TENT-B, in terms of separation of slag and ash, the optimal values of angle $\varphi = 30°$ and the angle $\beta=15°$ were determined. During the recording the amplitude-frequency (AF), the characteristic of the reconstructed VS, the value of the angle $\beta = 15°$ was set. The resulting excitation force amplitude setting was performed by setting the slewing angle α of eccentric flywheel masses in the range of $\alpha=5°\div175°$. The adjusting of the excitation force frequency was generated by the frequency power converter, or by changing the rotational speed of heavy flywheel mass. By changing the frequency of the electrical current of unbalanced motors in the range of 2Hz÷100 Hz, a change of the rotational speed in the range of 120÷1500 rev/min is achieved, while the change in frequency of excitation force is in the range 1Hz÷50Hz. The aim of experimental investigations in this case was to obtain the family of AF characteristics of VS for various values of the angle α. Based on these results, obtained by sub-resonance and super-resonance characteristics, i.e. function the vibration amplitude from the angle between the centre mass of eccentric flywheels, for various values of the excitation frequency.

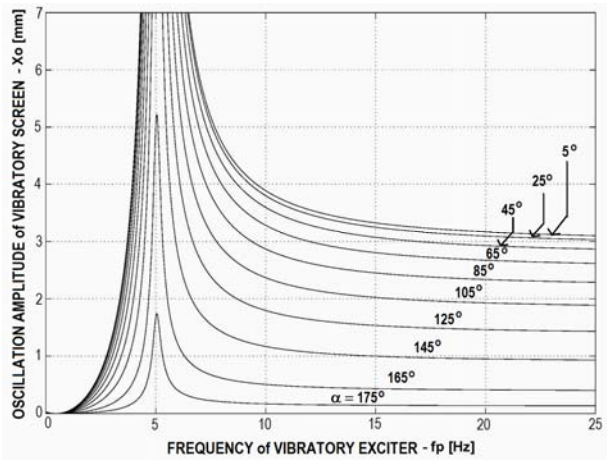

Figure 7. The family of amplitude-frequency (AF) characteristics of regulated drive of vibratory screens

Fig.7 shows the family recorded AF characteristics of VS with angle α as a parameter ($\alpha= 5°\div175°$). Obtained AF characteristics are very important because, based on them, we can determine the resonant frequency of the mechanical structure of the vibrating sieves and the range of amplitude change depending on the frequency, with the angle α as a parameter. It can be seen that the resonant frequency around $f_r=5$Hz ($\omega_r=31.4$ rad/s) at $\alpha=175°$ and that it slightly decreases with increasing of angle α. At the angle $\alpha=110°$ (rated angle for normal operation) the resonant frequency of $f_r=3.14$Hz ($\omega_r=19.7$ rad/s) was obtained. The operating point of VS must be significantly above the value (super-resonant range), because at that frequency there's has a significant increase in amplitude.

The functional dependence of the amplitude on the frequency (angle α as a parameter) in super-resonant range is given in Fig. 8.

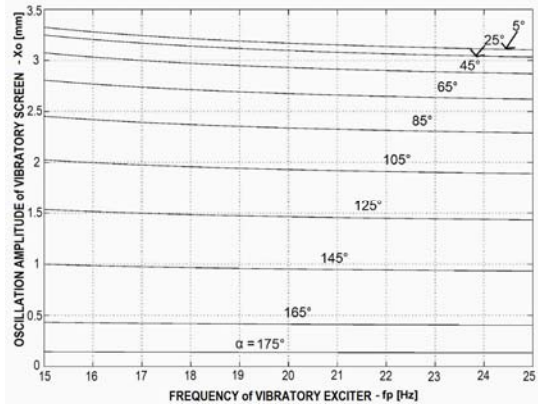

Figure 8. The family of amplitude-frequency (AF) characteristics of regulated drive of vibratory screens in the super-resonant range (operating characteristics)

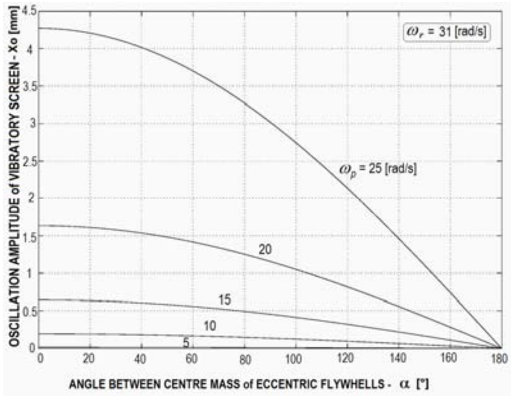

Figure 9. The sub-resonant characteristics of vibratory screen ($\omega_p<\omega_r$)

The Fig.8 shows that the amplitude of oscillation for a certain value of angle α does not depend on the frequency oscillation of VS, as was the case for the resonance range (Fig.7). The amplitude of the oscillation depends only on the angle α for each oscillation frequency.

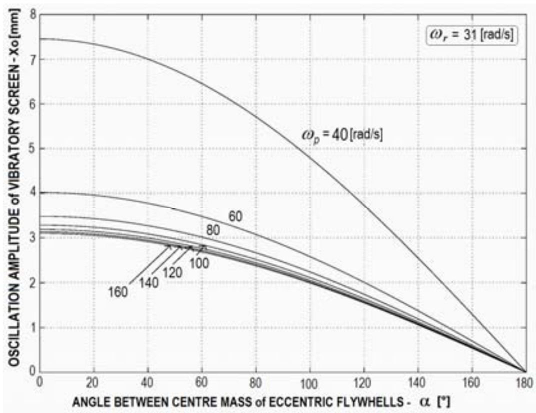

Figure 10. The super-resonant characteristics of vibratory screen ($\omega_p>\omega_r$)

It is noted that the AF characteristics in the frequency range 15-25Hz are approximately parallel and that with increasing angle α, the amplitude of oscillation of VS is reduced.

The Fig.9 shows the mathematically obtained dependence of oscillation amplitude of VS as a function of the angle α, with an exciting circular frequency ω_p, as a parameter of the angle α, for the sub-resonant range. The sub-resonant range relates to the low circular frequencies (ω_p= 5÷25 rad/s) and it is not of interest to the normal operation of VS. Significantly more interesting range for the operation of VS is the super-resonant range.

The Fig.11 shows the dependence of the VS oscillatory amplitude from the angle α for the super-resonant range. It can be seen that at a given value of the angle α, and the range ω_p=40÷60 rad/s, there's a significant "scattering" of characteristics and that the significant value of the amplitude of vibration can be obtained. The reason for this is that this range is close to the resonant frequency. For frequencies in the range of ω_p=80-160rad/s, the "scattering" of characteristics is significantly smaller, and the amplitude vibration as well. The reason for this is the relatively small changes of amplitude with frequency (shown in Fig.8). The rated operating point of VS is in this range, i.e. that the working amplitude is 2 mm (vibration width equal to twice the value of the amplitude i.e. 4mm) at circular frequency of ω_p=107.4 rad/s (f_p=17.1Hz) at the angle α=110°.

VI. Conclusion

In the paper is presents the implemented technical solution of electro-mechanical construction of vibratory screens and associated controlled drives in TENT-B, in the system for transport and disposal of slag and fly ash.

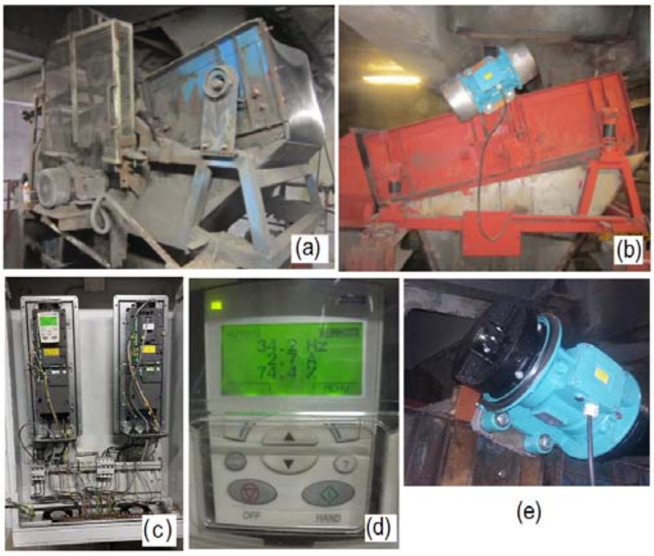

Figure 11. The real image show of realized regulated drive of one vibratory screen; (a) old system (unregulated drive), (b) new system with unbalanced vibratory excites, (c) frequency power converters FC1,FC2, (d) operator control panel (e) unbalanced motor with eccentric unbalanced flywheel.

The realized technical solution could be applied to all technological processes and process industries used for screening (the process of separating materials according to size, based on the geometric shape and size compared with the grain shape and size of the openings on the screening surface) and classification (separation of process materials and grains based on different speeds of movement of various granularity grains in a fluid). The mechanical construction and electrical control systems are implemented in VS with one storey, but there is no obstacle to the application on the systems for screening and classification that have multiple storeys. On Fig.11 the real recording pictures of regulated drive for one vibratory screen are shown. The old unregulated drive is shown in Fig.11 (a). The new realized system on TENT-B, with key elements, is shown on Figs.11 (b)-11(e).

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