Abstract: In addition to the high voltage power supply and drive electrostatic precipitator rappers, very important is the system to remove precipitated dust from the collecting hoppers which are located directly below the electrode system. Vibration of collecting hoppers appropriate amplitude and frequency can significantly improve the removal of precipitated dust. The vibratory actuators having electromagnetic drive are commonly used in these systems as a source of vibration. They are a standard controlled by thyristor converters. This converter is provided amplitude control of vibration and through it control of the flow collecting particles. Since these converters are synchronized to the 50Hz network, frequency of generated vibrations can be at 50Hz (single thyristor) or 100Hz (two thyristor in ant parallel). For the efficient flow and transport of separated particles is needed in addition to amplitude control to provide and frequency control of collecting hoppers. This paper presents one possible solution to the switching control of vibration actuator through IGBT converters which provided their amplitude and frequency control. Based on a simulation model of the system was developed experimental model, which shows the characteristic oscilloscopic records and confirmed the effectiveness of proposed solutions.

Key words: Electromagnetic actuator, dust removal, electrostatic precipitators, current control, vibration control, power converter, IGBT.

1. INTRODUCTION

The separation of particles of coal dust and ash significantly reduces the negative impact of waste materials that are the products of combustion in thermal power plants and heating plants. World standards that are becoming more accepted in our country require emission limit values (ELV) less than 50mg/m³, a tendency in the world is to reduce the level of the value of 25mg/m³.

Prevention of waste particles of coal dust and fly ash from the chimneys the mentioned plants, or their "collection" is achieved by electrostatic precipitator (ESP). The separation of the mentioned types of solid products is achieved by strong electrostatic field that forms in precipitation chamber of ESP.

In the precipitation chamber, there are two types of electrodes: collecting and emissions, as well as devices for rapping of separated particles. Periodic shaking of deposited material in the mentioned electrodes to exercise its accumulation in host hoppers (bunkers) which are located just below the precipitation chamber.

A typical distribution of ash in a percentage of a typical thermal power plant is shown in Fig.1. Approximately 10-15% of the ash is separated into the reception bunkers of boiler. On the exit of boiler, precisely from the bunker of economizer extract 5-10% of the ash. In a system for heating air extract about 2-5% of the ash. The ash from economizer and air heater is in fact on the fly ash and it is about 20% of the total quantity of ash. The rest of the ash in the flue gas passes...
through a system of high voltage electrode system of ESP, so that most of the ash 75-80%, is allocated in hoppers which are placed directly below high voltage precipitation chambers of ESP. A very small portion of ash, much less than 1% is extract at the bottom of the output chimney.

![Diagram of ash distribution in thermal power plant]

**Fig.1. Typical distribution of ash in thermal power plant**

From the reception hoppers of ESP, separated particles are continuously drain to different types of systems for evacuation and transport of ash. Depending on the fluid through which it transports these particles are different hydraulic and pneumatic transports. Hydraulic transport was done by water and pneumatic transport was done by gas, usually air.

Hydraulic transport is, in fact, a tubular transport of mixture deposited ash (particulate matter) and water. Hydraulic transport in case of removal of ash from ESP makes sense to use, considering that the ash does not change the physical properties or chemical reaction in contact with water. This is off the creation of compounds that could lead to a clogging of the pipeline.

With pneumatic transport, deposited ash can be transported without special restrictions. Hydraulic transport is used for longer distances, while air transport is used for smaller distances. Principally these types of transport are shown in Fig.2. Principally pneumatic transports of separated ash, from the ESP storage hoppers to a central discharge hopper, are shown in Fig.2 (a). The main drive to run the air is in fact one blower. The main flow of ash from the storage hopper is provided with rotary valves. The same is true for the case of hydraulic transport as shown in Figure 2 (b). In this case, the main transport medium of water and is therefore used as drive water pump. For both cases, it can be said that the flow of ash material can be further enhanced by the use of vibratory actuators that are placed at the bottom of the funnel as shown in Figs.2 (a), 2(b).

2. THE PHENOMENOLOGY OF VIBRATORY HOPPER DISCHARGE

Vibrating hoppers and bin are commonly used for transportation, processing or storage of bulk materials such as coal, grain, ashes, etc. Although hoppers are common, the internal flow of the material is not well understood, relying heavily on empirical information to maintain operation. For example, when a batch of material is introduced into a hopper for the first time, the material at the exit may arch and prevent flow. To remedy the situation, vibration may be used, sometimes in the crude form of a hammer, to perturb the material and initiate the flow [1].
Alternatively, the hopper may be equipped with a bin activator to continuously shake part of the hopper wall. These bin activators must be carefully designed to enhance the flow and not result in further settling or clogging of the material.

In the papers [2-5] is prove that horizontal vibration increased the mass discharge rate as compared with the discharge rate from a hopper without vibration and that the increase depended on the vibration velocity amplitude. In addition, the discharging granular material flows from alternating sides of the hopper producing an inverted funnel pattern.

In addition to horizontal vibration, the storage and discharge hoppers can be subjected to vertical vibrations. In the paper [2], which relies on the investigation on paper [1], the research is aimed at experimental and simulation results of the vertical vibration effect on the flow of materials in planar vibratory hopper.

The discharge of granular material from a hopper subject to vertical sinusoidal oscillations was investigated using experiments and discrete element computer simulations. With the hopper exit closed, side-wall convection cells are observed oriented such that particles move up along the inclined walls of the hopper and down at the center line. The convection cells are a result of the granular bed dilation during free fall and the subsequent interaction with the hopper walls [1], [6].

Over the last decade, the effect of vertical vibration on a bulk material in hoppers and bins has been studied extensively. For a hopper box that is vibrated sinusoidally, \( z = Z_m \sin(\omega t) \) where \( Z_m \) is the amplitude of vibration and \( \omega \) is the radian frequency, the bed of hopper exhibits several different flow patterns depending on the dimensionless acceleration amplitude, \( \Gamma = Z_m \cdot \omega^2 / g \) where \( g \) is the gravitational constant, and the frequency \( f = \omega / 2\pi \). For \( \Gamma > 1 \), side-wall convection cells
appear where particles move down along vertical hopper walls and up within the remainder of the hopper. Standing waves, forming at one-half the forcing frequency, appear on the free surface of the bed for $3.5 > \Gamma > 2.2$ and waves forming at one-quarter the forcing frequency occur for $\Gamma > 5.5$. Neighboring regions of the particle bed can oscillate out-of-phase, termed ‘‘kink waves,’’ for $\Gamma > 3.5$ with counter-rotating ‘‘kink convection cells’’ bracketing each wave node. The paper by Wassgren et al. [6] describes these phenomena in greater detail.

The effects of vertical vibration on flow from wedge shaped hoppers and flat bottom bins were first examined in papers [7-8]. These investigations are focused on the appearance of convection cells near the inclined wall boundaries of the hopper. Also, the discharge rate was shown to increase with vibratory frequency at a fixed level of acceleration, but at the highest accelerations the discharge rate decreased significantly. Vibration also induced flow in bins that could not discharge under gravity alone.

The flow from vertically oscillated funnels with small exit widths and wall angles are studied in [9]. In this research it was determined that the dimensionless acceleration amplitude, $\Gamma$, and wall angle $\alpha$ (as measured from the hopper centerline) significantly affect how particles ‘‘jam’’ or mechanically arch at the exit.

Without vibration, the mass discharge rate from a hopper, $W$, is proportional to the bulk density of the bed near the hopper exit, $\rho_b$, the square root of the acceleration acting on the bed, $g$ (the acceleration due to gravity) and the hydraulic diameter of the hopper exit, $D_h$ raised to the $5/2$ power:

$$ W \sim \rho_b \cdot g^{1/2} \cdot D_h^{5/2} $$

To predict trends in the discharge rate under influence on vertical vibration in [8] is proposed a simple model that includes the variation of the ‘‘effective gravity’’ acting on the granular material over an oscillation cycle. Since the hopper is oscillating, the effective gravity the bed experiences relative to the hopper walls, $g_{eff}$, will vary throughout an oscillation cycle as:

$$ g_{eff} = g \cdot [1 - \Gamma \cdot \sin \omega t], \quad \Gamma \leq 1 $$

If the acceleration amplitude of the oscillations is greater than one ($\Gamma > 1$) the bed leaves the hopper walls during a portion of the oscillation cycle and contacts the walls at some later time. The equations originally derived by Suzuki et al. [8], also included an empirically derived expression for the bulk density of the bed as a function of $\Gamma$:

$$ g_{eff} = \begin{cases} 
  g \cdot [1 - \Gamma \cdot \sin \omega t] \\
  0 \\
  y_b 
\end{cases} $$

Precisely, $g_{eff} = g \cdot [1 - \Gamma \cdot \sin \omega t]$, when the bed rests on the hopper walls, $g_{eff} = 0$, when the bed is flight and $g_{eff} = y_b$, when bed just impacts the hopper walls. The acceleration $y_b$ presents the acceleration acting on the bed at impact and it is approximately equal to the difference between the floor velocity at impact and the particle bed free fall velocity just prior to impact divided by the duration of the impact period.

In study [8] is assumed that the discharge rate to be a function of the instantaneous ‘‘effective gravity’’ acting on the particle bed. In their model, Suzuki et al. suggest that the instantaneous discharge rate from the hopper is given by:

$$ W \sim \rho_b \cdot g_{eff}^{1/2} \cdot D_h^{5/2} $$

Suzuki et al. also propose that the only vibration parameter on which the bulk density of the material, $\rho_b$, should depend is the dimensionless acceleration, $\Gamma$, with the bulk density increasing when vibration is applied[8].
As for the excitation frequency of hopper oscillations that are used in the effective materials dose and the extraction has to be said that they are dependent on their bulk density. For light and elastic bulk materials (bulk densities less than 0.5 kg/dm³) lower frequencies (750-1500 oscillations per minute) are preferred, while materials with higher bulk densities generally require higher frequencies (1500-3000 oscillations per minute). Certain dosing hoppers (with small dimensions) have been designed to convey material at even 6000 oscillations per minute. However, very often the exception becomes the rule. Other factors such as humidity can drastically change the theoretical parameters of conveyor design.

3. ELECTROMAGNETIC ACTUATOR FOR EXCITING OF VIBRATORY HOPPER

Different drive types can achieve mechanical vibrations of the vibratory hopper. The very first drives were originally mechanical (pneumatics, hydraulics, and inertial). Today, most of the common drives are electrical.

When a reciprocating motion has to be electrically produced, the use of a rotary electric motor with a suitable transmission is really a rather round-about way of solving the problem. It is generally a better solution to look for an incremental-motion system with magnetic coupling, so-called “electromagnetic vibratory actuator” (EVA), which produces a direct “to-and-from” movement [10].

Electromagnetic drives offer easy and simple control for the mass flow of particulate and bulk materials. In comparison to all previously mentioned drives, these have a more simple construction and they are compact, robust, and reliable in operation. The absence of wearing mechanical parts, such as gears, cams belts, bearings, eccentrics, or motors, makes vibratory conveyors, hoppers, feeders etc. most economical equipment [11]–[13].

Fig. 3. The electromechanical system for exciting vibratory hopper for efficient dust particulate flow (a) mechanical construction, (b) armature of EVA on active side, (b) armature EVA on reactive side

On Fig. 3 is show a typical design of vibratory hopper which is excited by three electromagnetic actuators EVA-1 … EVA-3. Vibrating hopper is elastically supported by ESP plant
construction. The material is transported into the hopper is in fact fly ash obtained by rapping of the collecting ad emission plates of ESP. Vibrating actuators are mounted on the sides near the bottom of the vibrating hopper, forming a triangular shape. In this way, the entire mechanical construction becomes oscillatory system with two-masses: one consisting of vibrating hopper filled with ash, the total mass $M$ and the other consisting of a moving part of EVA, whose mass is $m$. The actuators are placed at an angle of $120^\circ$ relative one to another, so that the horizontal component of their excitation forces $F_h$ are canceled, while their vertical components add up and give the resultant excitation force $\sum F_i$, as shown in Fig. 3 (a).

All main types of vibratory hoppers can be seen as two-mass systems. The majority of them generate harmonic excitation forces, while some types generate transmitting impact pulses. The EVA can be single- or double-stroke construction. In the single-stroke type, there is an electromagnet, whose armature is attracted in one direction, while the reverse stroke is completed by restoring elastic forces. In the two-stroke type, two electro-magnets, which alternately attract the armature in different directions, are used.

In Fig.3 two of the most common single-stroke constructions are shown. One of them has armature on its active side, while inductor is on its reactive side, as shown in Fig. 3(b). The other construction is set vice versa, as shown in Fig. 3(c).

The mathematical model of EVA is based on presentation in reference [10] with details. An electromagnet is connected to an ac source and the reactive section is mounted on an elastic system of springs. During each half period when the maximum value of the current is reached, the armature is attracted, and at a small current value it is repelled as a result of the restoring elastic forces in springs. Therefore, vibratory frequency is double frequency of the power supply.

These reactive vibrators can also operate on interrupted pulsating (DC) current. Their frequency in this case depends on the pulse frequency of the DC. Mechanical force, which is a consequence of pulsating current and created by electromechanical conversion in the EVA, is transmitted through the elastic springs to the outer wall of the hopper.

4. POWER CONVERTER FOR EXCITING OF EVA

By a suitable control of the vibratory bin discharger’s excitation force, which is obtained by means of EVA, it is possible to accomplish control of their acceleration and consequently control of the discharge rate of transporting material from hopper.

![Fig.4. Phase controlled thyristor converter for driving vibratory hoppers; (a) unidirectional topology and (b) waveforms of the EVA current and voltage](image-url)
In this way the whole conveyance system behaves like a fully controlled mechanical oscillator. For most of the vibratory conveying drives of this type the range of amplitudes of acceleration are from 0.1g up to 10g and the range of operating frequencies is from 20Hz up to 150Hz, depending upon the type of the conveying material and load [14].

Application of vibratory discharge hoppers drives in combination with power converters provides a significant flexibility in fulfilling the requirements for efficient flow and conveyance of granular materials. At present, thyristors and triacs are used as standard semiconductor output power stages for driving electromagnetic vibratory actuators. Their application implies adjustment of vibratory width (double amplitude of the oscillations) of the walls hopper by means of phase control, i.e. regulation of the phase angle $\alpha$. Basic topologies of the standard power converters, together with the corresponding waveforms of the EVA current and voltage, are shown in Figs. 4 and 5.

One type of these converters – unidirectional, having pulsating DC output current, makes use of only one half-period of the mains voltage. It is realized by using one thyristor, as shown in Fig. 4(a). In this type of converter the thyristor is triggered only during positive half-periods, as indicated in Fig. 4(b). In this way the mains voltage of frequency 50(60) Hz at the input of the converter is converted to a pulsating direct current (DC) which supplies EVA coil. By applying this control it is possible to obtain a discrete frequency spectrum of the input current: 50(60)Hz, 25(30)Hz, 16.66(20)Hz, 12.5(15)Hz, 10(12)Hz, 8.33(10)Hz, i.e. a spectrum of discrete vibrations of LCE: 3000(3600) cycles/min, 1500(1800) cycles/min, 1000(1200) cycles/min, 750(900) cycles/min, 600(720) cycles/min, 500(600) cycles/min.

Another type of converter-bidirectional or alternating output current converters, make use of both half-periods of the mains voltage. It is designed by using triacs and, by using anti-parallel connection of thyristors for high powers, as shown in Fig. 5(a). With this type of converter the mains voltage of frequency 50(60) Hz is converted to an alternating current of the frequency which is the same as the one which supplies EVA coil, as shown in Fig. 5(b).

Since the excitation force of EVA coil is function of the square current flowing through the coil [10], with the first type of converters one generates excitation force of the maximum frequency 50(60) Hz producing vibrations of 3000(3600) cycles/min, whereas with the second type of converter the maximum frequency of the excitation force is 100(120) Hz producing vibrations of 6000(7200) cycles/min.

It should be noted that under the effect of vibration, in the real case, the most exposed EVA elastic elements or springs. If, for example, daily dischargers operate for about 8 hours with 3000 cycles/minute, then the number of cycles of loading-unloading in the spring about 1.5 million cycles.

Fig.5. Phase controlled thyristor converter for driving vibratoryhoppers; (a) bidirectional topology and (b) waveforms of the EVA current and voltage.
per day. This can lead to significant degradation and changes in the spring, and consequently to its stiffness.

Application of the phase controlled thyristor or triac converters in vibratory discharging implies a fixed frequency of vibrations, imposed by the supply network frequency. A serious problem arises when the characteristic of the EVA springs has changed, i.e. mechanical resonance has changed. In such case the vibratory system will not operate efficiently. It is possible to tune amplitude but not the frequency of the vibrations. Variation of the spring characteristics leads to reduction of efficiency of the electromagnetic vibratory drives. In order to accomplish an optimal and efficient operation at a new resonant frequency, it is necessary to change the frequency of EVA supply current.

The work on application of high-frequency (HF) transistor converters for obtaining sinusoidal current through EVA coil has been intensified recently. Like with thyristor converters, one can talk of unidirectional and bidirectional types, depending whether a pulsating DC current or an alternating excitation current is accomplished [10], [14]. Mainly, the three topologies, shown in Fig. 6, have been accepted.

![Fig.6. Switching converter topologies for EVA excitation; (a) asymmetric half-bridge, (b) symmetric half-bridge and (c) full-bridge.](image)

The topology consisting of two switches and two return diodes is used in designing the unidirectional type of converters, i.e. the asymmetric half-bridge shown in Fig.6(a), while the half-bridge and full-bridge topologies, shown in Figs. 6(b) and 6(c), respectively, are used for designing the bidirectional type of converters.

The required sine-wave (half-wave) can be realized by these topologies if the applied current control is based on tracking the reference sine-wave of adjustable length, amplitude, and frequency. This method of generation of the excitation current has the advantage in that it allows independent tuning of the frequency and amplitude of the electromagnetic excitation force F.

The switching converter described in [10], despite its advantages, suffers from a serious shortcoming that at high frequencies its switching losses become dominant. In addition to these losses, the losses in iron of the magnetic circuit and in copper of EVA coil become also significant. This reduces the efficiency of the whole electromechanical system and it is not unusual that the power of losses in the system power converter-EVA-hopper is higher than the power required for maintaining the resonant oscillatory mode. This reduces considerably the efficiency of the drive as a whole. By a suitable control of the switches in these topologies, it is possible to overcome this problem and accomplish the expected vibratory effect, i.e. the required amplitude of oscillations and optimal operating frequency of the vibratory hopper.
The strategy of current control by means of a switching converter is generally known in power electronics applications of power supplies. Similar principle has been used for EVA excitation since it represents, as already shown, a predominantly inductive load \( \frac{L_0}{R_c} \gg T_d \).

The principle diagram of the current control is shown in Fig. 7. The control circuit which provides control of the amplitude, length, and frequency of the triangular current half-wave is shown in Fig. 7(a). The characteristic waveforms are shown in Fig. 7(b). Control of the current pulse strength is accomplished by a current control loop. Instantaneous value of the actuator current \( i(t) \) is measured by the corresponding current sensor. The measured signal is amplified by factor \( K_i \) and the amplified signal is fed to an adder where it is compared with the reference value \( I_{M_{ref}} \) of the amplitude of the current.

Setting the RS flip-flop FF is accomplished from a voltage controlled oscillator. By feeding signal from the oscillator to S input of flip-flop FF, the state of logical “1” is established at its output \( Q \) (output \( Q \) is at the state of logical “0”), i.e. switches \( Q_1 \) and \( Q_2 \) are turned on simultaneously.

This establishes the current through EVA coil in the form a growing ramp since voltage \( +V_s \), is applied across the coil terminals. The growth continues until the instantaneous current value reaches the reference value \( I_{M_{ref}} \), when the RESET pulse is generated at R input of flip-flop FF.

The state of logical “0” is established at its output \( Q \). As this state is established, switches \( Q_1 \) and \( Q_2 \) are turned off simultaneously, and current of the coil is taken over by return diodes \( D_1 \) and \( D_2 \). EVA current decreases linearly since voltage \( -V_s \) is applied at the coil terminals. The state of reset is maintained until a new SET pulse arrives from the oscillator. The amplitude and duration of the current are determined by the instant when instantaneous value of the current reaches value \( I_{M_{ref}} \).

5. DESCRIPTION OF EXPERIMENTAL PROTOTYPE OF IGBT CONVERTER

A practically realized IGBT transistor converter for excitation of a vibratory hopper having electromagnetic excitation is described in this section. Fig. 8 shows block diagram of the complete system.

Transistor converter comprises two power converters. One is input AC/DC converter with power factor correction (PFC), while the other one is DC/DC (pulsating current) converter for driving EVA. Input converter is in fact a controllable transistor rectifier with two “boost” stages.
and inductance on the AC side. This converter with advantages over the conventional power factor corrector (diode bridge rectifier-power switch-diode-inductance on DC side) is described in detail, in [15] and [16].

Fig.8. Block diagram of the acceleration control of vibratory hopper with IGBT power converter

The output converter for excitation of EVA coil, realized by using the asymmetric half-bridge – (1), consists of two IGBT transistors $Q_1$ and $Q_2$ positioned in one diagonal of the bridge and two return diodes $D_1$ and $D_2$ positioned in the other diagonal. Excitation of the IGBT’s is accomplished by the driving circuit – (2) which contains two independent channels for driving the upper and lower transistors. Driving the upper transistor is realized by a „floating“ circuit which can sustain high voltage and is immune to sharp voltage edges ("$dv/dt$".). The control part – (3) is based on industrial DSP controller where the algorithms for search and tracking of the resonant frequency are implemented, together with current control, tuning amplitude of the oscillations, etc. The controller as well as the circuit for monitoring the voltage if the intermediate DC circuit are galvanic isolated by opto-couplers – (4) from the power part of the IGBT converter. The value of EVA current is measured by a Hall effect current sensor, the so called LEM current sensor – (5). Discharge of the electrolytic capacitors in the intermediate DC circuit is carried out via resistor $R_b$ and transistor $Q_3$ which is controlled by the voltage monitor – (6) containing a built-in hysteresis, which "observes"voltage of the DC circuit $V_s$ and compares it with the set threshold $V_{trip}$.

The over-current and over-load protection circuit is realized by the current protection - (7) block. The „intervening“system of protection is applied. Under normal conditions, the load current is programmed by the controller. In the case of a direct short circuit or overload, block (7) takes over. Measurement of the output displacement of the moving part of EVA and detection of its passage through the equilibrium position is accomplished by a non-contact inductive displacement sensor – (8), operating in the displacement range ±5mm and frequency range 0-1kHz. The signal of this sensor is transmitted by an electronic amplifier – (9) and normalized to the 0-1V level. The vibratory acceleration of the hopper is measured by inductive acceleration sensor-(10), which has...
$B12/500 - HBM$ type for acceleration range $0 - 1000m/s^2 \ (0 - 10g)$ and for frequency range $0 - 200Hz$. The signal of this sensor is transmitted by an electronic transmitter– (11) and normalized to the 0-1V level.

6. EXPERIMENTAL RESULTS

In this section some experimental results are presented. These results are recorded on the real experimental control systems of IGBT power converter for driving one real vibratory hopper. Experiments described below were performed under the following conditions:

Mass of moving parts of each actuator (total there were 3 pieces) was $m = 3kg$, and the mass of hopper without material was $M_o = 600kg$. The mass of material depending on the operating mode has been variable in the range 0-5400kg. The observed material is a silicate ash density of about 2000kg/m$^3$. The whole vibrating basket was subjected to vertical vibration under the action of the actuator and corresponding IGBT converter.

Fig.9. Adjustment of vertical component acceleration amplitude of vibratory hopper means of current controlled IGBT converter; (a) duty cycle $\delta = 15\%$, (b) duty cycle $\delta = 30\%$

On the oscilloscopic records in Fig.9 are presented the waveforms of current and voltage of EVA and vertical components of the acceleration $\ddot{z}(t)$ of vibratory hopper. The vibratory hopper is filled with material having mass $M = 4t$. The moving part of EVA weighed $m = 3kg$. Resonant frequency of vibratory hopper was $F_{res} = 25Hz$.

In Fig.9 (a), at the duty cycle $\delta = 15\%$ of current controlled IGBT converter has been shown that the amplitude of acceleration $\ddot{z}(t)$ was $a_{com} = 1g$ (i.e. peak to peak acceleration $a_{pp} = 2g$).

In Fig.9 (b), at the duty cycle $\delta = 30\%$ amplitude of acceleration $\ddot{z}(t)$ was $a_{com} = 4g$ (i.e. peak to peak acceleration $a_{pp} = 8g$). Under these conditions, the oscillation frequency was 100 Hz, so that the vibrating bin exercised vibrations with very small amplitude (less than 0.1mm).

In Figure 10 are presented oscilloscopic recordings relating to the compensation effect of changes in the resonant frequency of the EVA, which emerged as a result of the degradation of elastic elements (springs) in it.

The first experiment was performed with the EVA with a resonance frequency of $F_{res} = 100Hz$ i.e. which is equivalent to the stiffness of the elastic element was $k = 1.18kN/mm$.

This mode is shown of oscilloscopic records driving current of EVA and acceleration of vibratory hopper, as shown in Figure 3(a). At the amplitude of EVA current of 8.2A and time duration of 5ms, vibrating hopper is oscillating with frequency 100Hz and amplitude of the acceleration of 3g.
Fig. 10. Frequency control of EVA for compensation of drift characteristic of springs: (a) stiffness of EVA springs $k = 1.18 \text{kN/mm}$, $F_{drv} = F_{res} = 100 \text{Hz}$, (b) stiffness of EVA springs $k = 1.12 \text{kN/mm}$, $F_{drv} = 100 \text{Hz}, F_{res} = 97.6 \text{Hz}$, (c) stiffness of EVA springs $k = 1.12 \text{kN/mm}$, $F_{drv} = F_{res} = 97.6 \text{Hz}$.

In Fig. 10(b) are presented waveforms when using actuators that have already achieved a significant number of operating cycles so that his spring fell by about 5% (decreased their stiffness $k = 1.18 \text{kN/mm} \rightarrow k' = 1.12 \text{kN/mm}$), which resulted in reduction of the resonant frequency of about 2.5 Hz. It is observed that if the excitation remains the same, there was a significant reduction in the intensity oscillations of vibratory hopper, and hence the amplitude of the acceleration, so that in this case it was 0.4g.

The Influence of compensation drift characteristics of elastic elements is shown in oscillographic records on Fig. 10(c), from which shows that the excitation frequency fully complies with the new resonant frequency. As a result of this new regime was achieved with amplitude of acceleration of 10g, which had at beginning of experiment. Amplitude of the EVA current was 8.5A when its duration is amounted about 6ms.

Fig. 11. Relative discharge rate from oscillating hopper plotted as a function relative acceleration amplitude $\Gamma$.

In the experiments the mean discharge rate $W$ from the hopper, was measured over the range of driving frequency and vertical component of acceleration. Experimentally obtained discharge rates are normalized by the mean discharge rate $W_0$ for non vibrating hopper, and are presented in Fig. 11, as function relative acceleration amplitude $\Gamma = \frac{Z_m \cdot \omega^2}{g}$. The discharge rate for frequencies below 50Hz decrease with increasing of relative acceleration of hopper. For frequencies 60Hz and 80Hz, the relative discharge rate is approximately equal or slightly greater than unity, but at the frequency 100Hz is observed a significant increase discharge rate of 20%.
7. CONCLUSIONS

The paper presents a possible solution for the amplitude and frequency control of electromagnetic vibratory actuator applied to vibratory hopper excitation. The solution of IGBT power converter represents a considerable improvement compared to the conventional, phase controlled thyristor and triac drives. The basic shortcoming of the phase control is that it can only tune amplitude of the oscillations of moving part of actuator but not their frequency.

The proposed EVA current control is based on the switching topology. This topology offers numerous advantages with respect to the conventional thyristor topology. The most significant advantage is the possibility of independent tuning of the amplitude and frequency of oscillations. As a result, it is now possible to track the resonant mode of a vibratory conveyance system with sufficient speed and precision.

The presented experimental results have shown that EVA current control resulted in a very efficient method for both amplitude and frequency control, which is essential for tuning the acceleration amplitude of vibratory hopper, which maintains the resonant mode of the EVA. The resonant mode is very important from the point of view of energy efficiency and minimization of energy consumption of the whole vibratory drive.

In experiment are presented results relating to the compensation effect of changes in the resonant frequency of the EVA, which emerged as a result of the degradation of elastic elements (springs).

Also, in experimental investigations have shower that the relative discharge rate from vibrating hopper decrease for low frequency, with increasing of relative acceleration of hopper. For frequencies 60Hz and 80Hz, the relative discharge rate is approximately equal or slightly greater than unity, but at the frequency 100Hz is observed a significant increase discharge rate of 20%.

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REFERENCES


