A Comparison of Energy Efficiency of SCR Phase Control and Switch Mode Regulated Vibratory Conveying Drives

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Abstract— **Vibratory conveying drives having electromagnetic excitation provide easy and efficient control of particulate materials flow. The achievement of variable intensity and frequency of vibration in a wide range, through adequate power converters ensures the continuous material flow under different operating conditions. Today, as a standard power stage for supplying regulated vibratory conveying drives (RVCD), SCR devices have been used. This implies the use of phase control and fixed excitation frequency 50Hz (i.e. frequency of power supply network). Consequently, with these converters only the change in oscillation amplitude of conveyor can be achieved, by changing the phase angle, while the change of the frequency of oscillation is not possible. Switch mode power converters, in addition to amplitude control, provide the frequency control. In this way the RVCD is independent of the network frequency. Frequency control provides operation of vibratory conveyors in the region of mechanical resonance. Operation in this region is the most energy efficient because the entire RVCD has minimal power consumption. This paper presents a comparison of practically implemented phase control SCR and switch mode IGBT power converters used in RVCD and corresponding experimental results, from the stand point of energy efficiency.**

Keywords- Vibratory conveyor, resonance, power converter, SCR, IGBT, energy efficiency

I. INTRODUCTION

Vibratory conveyors having electromagnetic drive are widely used devices for transport of particulate material in various technological processes such as gravimetric transport, compacting, shaking, processing, dosing, etc.

From the macroscopic view, the process of vibratory transport is based on micro-throws of particles of the material being conveyed [1-4]. Vibrations of the trough, i.e. *load carrying element* (LCE), containing the material, cause bouncing of material particles. Therefore the material obtains character of a viscous fluid and so becomes suitable for conveying or further processing.

Operation of electromagnetic vibratory conveying drives in the mechanical resonant range becomes favorable, because the final values of the amplitude of the oscillation, can be obtained for relatively small energy of excitation.

The electromagnetic drives are very popular, because of their high efficiency and easy maintenance. This drives are based on the electromagnetic vibratory actuator (EVA).

By realizing free vibrations of variable amplitude and frequency, over a wide range through application of the EVA, suitable power converter and the corresponding controller, continuous conveyance and dosing of granular materials have been provided for various operating conditions. In this way, the whole system *power converter-EVA-vibratory conveyor* i.e. regulated vibratory conveying drive (RVCD), has a behavior of the controllable mechanical oscillator [5-6].

Standard power output stages intended for RVCD, using SCR devices (thyristors and triacs), imply the use of phase angle control. Since the supply network frequency is constant (50Hz/60Hz), the adjusting of phase angle can only accomplished tuning of the amplitude oscillations, but not their frequency.

Application of switch mode IGBT power converters enables accomplishing the amplitude and/or frequency control of vibratory conveying. Their use makes the excitation of a vibratory conveyor independent of the supply network frequency. In addition, the control of frequency ensures operation of vibratory conveyors in the region of mechanical resonance.

Operation in this region is the most energy efficient, since then, the entire RVCD has minimal power consumption. The research presented in this paper clearly establishes the comparison of concretely implemented conventional phase control and switch mode IGBT transistor power converter used to RVCD and shows experimental results from the point of increasing energy efficiency.

II. THE RESONANCE EFFECT IN RVCD

For most technical systems operation in the resonance range is unfavorable because it can lead to significant stresses and fracture of mechanical construction, since in this case, for small values of excitation forces, amplitude of oscillations get very large. The limitation of the amplitude oscillations can be achieved by appropriate control of excitation force.

A typical arrangement of resonant vibratory conveyor with electromagnetic drive is presented in Figure 1. Its main components are: *load carry element* -1, EVA as source of excitation force F and *flexible elements* -2. Flexible elements are made of composite leaf (fiberglass) springs. These elements are rigidly connected with the LCE on the one side, while, on the other side, they are fitted to the *base*-3 of the device and sloped down under certain angle. The base of vibratory conveyor is resting on *rubber pads*-4 to the foundation. EVA consists of a *magnetic core*-5, covered by continuous *windings coil*-6. As the ferromagnetic material has a very high permeability, all energy of the magnetic field is stored in air gap. Created magnetic field which produce the electromagnetic force F acts on *armature*-7 attached to the LCE. This element carries the *vibratory trough*-8 along with conveying material.

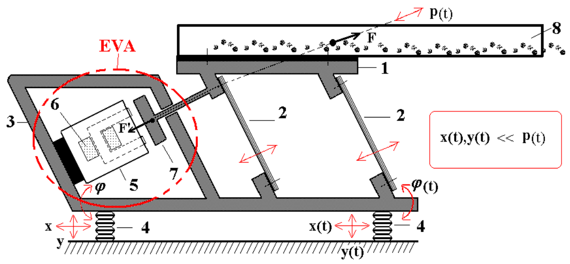

Figure 1. Typical arangement of resonant vibratory conveyor having electromagnetic drive

Displacement $p(t)$ of LCE is dominant and much larger then vertical and horizontal displacements of base $x(t)$ and $y(t)$, respectively. Taking into account the dominant influence of flexible elements (whose characteristics are: stiffness-k and damping-β) on the oscillations of vibrating system whose mass is m, it is possible to replace a mechanical system represented with 4 DOF with state variables p, x, y and φ, with a simplified mechanical system with 1 DOF, as shown in Figure 2.

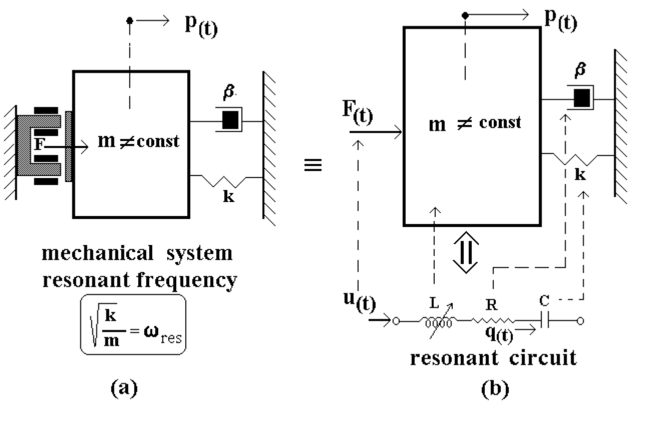

Figure 2. Simplified electromechanical presentation of resonant vibratory conveyor with electromagnetic drive; (a) mechanical presentation , (b) resonant electrical circuit

Detailed dynamic model of resonant conveyor on Fig.1 is given in [5-6], taking into account several oscillating modes. It should be mentioned that in the range of vibrations of interest, all four modes are not needed. In practical applications the largest contribution to moving the LCE has the oscillatory mode with frequency $\omega = \omega_{res}$, coming from high quality composite springs [7-8].

III. Power Converters in RVCD

Application of resonant vibratory conveyors in combination with power converters provides a significant flexibility in fulfilling the requirements for conveyance of granular materials. At present, SCR devices (thyristors and triacs) are used as standard semiconductor output power stages for driving electromagnetic vibratory conveyors. Their application implies adjustment of vibratory width (double amplitude of the oscillations) of the LCE by means of phase control, i.e. by regulation of the phase angle α [5-6], [9-10].

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. In this type of converter the tyhristor is triggered only during positive half-periods. In this way the mains voltage of frequency 50(60) Hz at the input of the converter is converted to a pulsating dc current which supplies EVA coil. By applying this control it is possible o obtain a discrete frequency spectrum of the EVA 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 [11].

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 (for low powers) and, by anti-parallel connection of thyristors (for high powers).

Through this type of converter, the mains voltage of frequency 50(60) Hz is converted to an alternating current of the same frequency, by which is supplied EVA coil.

Since the excitation force of EVA coil is function of the square current, flowing through the coil [9-10], 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 [11].

The phase controlled SCR converters in RVCD implies a fixed frequency of vibrations, imposed by the supply network frequency. A serious problem arises when the mass of the conveying material is changed, i.e. mechanical resonance of the system 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. In addition, the thyristor converter brings in a dc component and undesirable higher harmonics. Application of triacs results in somewhat better situation as regards the harmonic content, but the same problem arises if the resonant frequency is changed.

Variation of the mechanical resonance due to variation of the mass of the conveyed material, or even variation of the system parameters (characteristics of the springs, damping, etc.), leads to reduction of efficiency of the 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, i.e. the frequency of the excitation force of the vibratory conveyor.

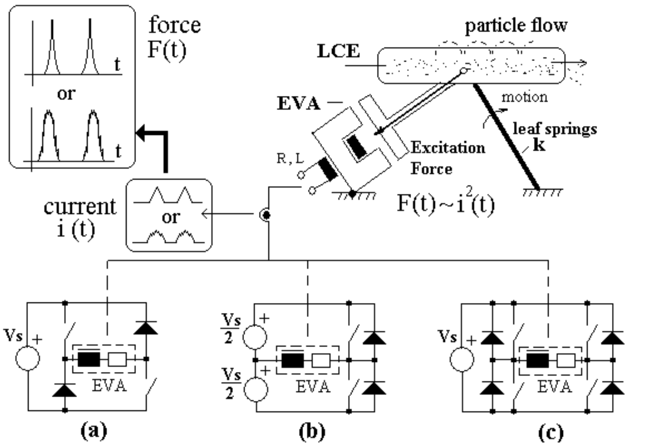

Figure 3. Switch mode power converter topologies for EVA excitation; (a) dual forward , (b) half bridge and (c) full bridge

The work on application of switch mode 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 or an ac excitation is accomplished [8-9]. Mainly three topologies have been accepted, shown in Figure 3.

The topology consisting of two switches and two return diodes is used in designing the unidirectional type of converter, i.e. two switch forward converters or dual forward converter [12-13]. The half-bridge and full-bridge topologies 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 [9]. 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 $F(t)$.

The switching converter described in [9], despite its advantages, suffers from a serious shortcoming that at high frequencies its switching losses become dominant. In addition, the losses in iron of the magnetic circuit and in copper of EVA coil become also significant. This reduces the efficiency of the vibratory conveyor and it is not unusual that the power of losses in the RVCD is higher than the power required for maintaining the resonant oscillatory mode. This reduces considerably the efficiency of the whole vibratory conveying drive.

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 LCE oscillations and optimal operating frequency of RVCD [11].

The next chapter will present an experimental setup in which the phase control SCR and switch mode power converters are properly compared, with a focus on energy efficiency of whole RVCD.

IV. The Experimetal Setup for Comparison Of Phase Control and Switch Mode RVCD

In order to study the influence of the resonance on the energy efficiency of the phase control and switch mode RVCD, corresponding power converters and mechanical drive are realized. Energy efficiency comparison of the two types of RVCD's was performed under the same conditions and in both cases the following quantities were measured: current and voltage of EVA, EVA power, mains voltage, input current and input power. Also, it is measured the output displacement of LCE of vibratory conveyors. Experimental setup for these cases is shown on Figure 4.

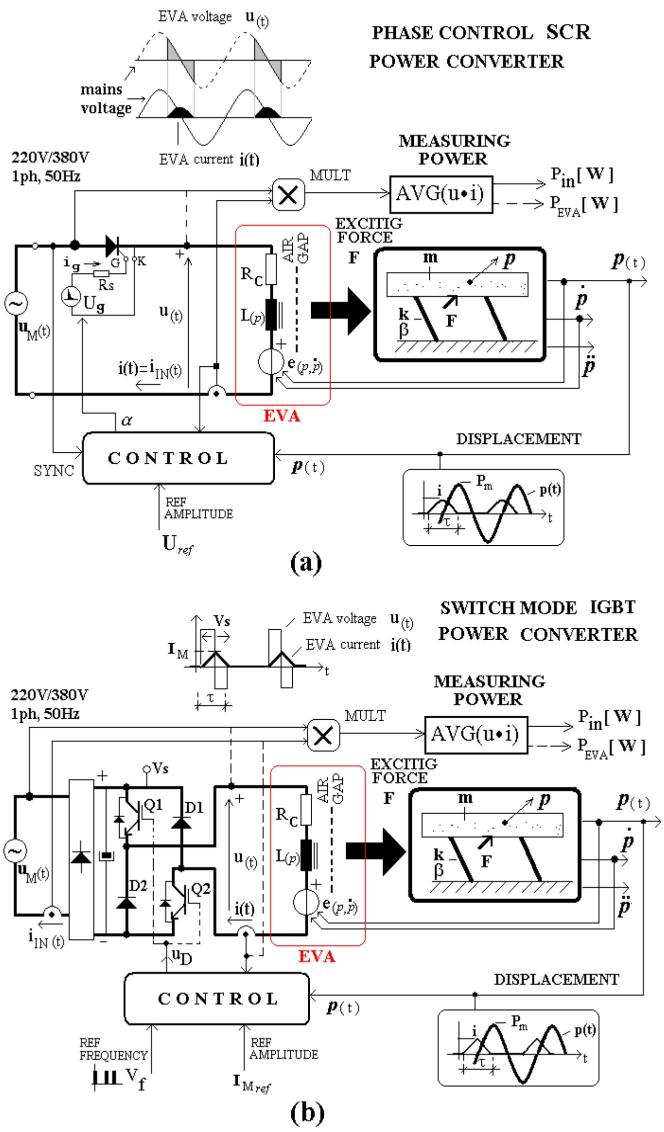

Figure 4. Experimental setup for comparison of energy efficiency of RVCD; (a) phase control SCR power converter and (b) dual forward (two switch) IGBT converter

A practically realized phase control SCR power converter of RVCD, having phase control, is shown on Figure 4(a). It consists of thyristor half-wave rectifier and associate control circuit. By this setup a voltage control of EVA is provided. In this way, it simply enables control of output amplitude of LCE. The driving frequency is constant and determined by the mains 220V/380V, 50Hz. The adjusting of the EVA voltage is provided via a reference input signal U_{ref}. The output control variable is the phase angle α, with the changes achieved in the range 60º-175º.

A practically realized switch mode IGBT transistor converter for excitation of a vibratory conveyor having electromagnetic excitation is described in this section. Figure 4(b) shows block diagram of the complete system. This power converter consists of an input single phase ac/dc voltage source 220/380V, 50Hz to $V_s = 400VDC$ and switch mode IGBT converter which serves for generation of the pulsating DC excitation current.

The output converter for excitation of EVA coil, realized by using the dual forward converter, 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 which contains two independent channels for driving the upper and lower transistor. 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 is based on industrial PC104 module 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 and the circuit for monitoring the voltage of the intermediate DC circuit are galvanic isolated by opto-couplers from the power part of the converter.

In both presented experimental setup all the necessary measurements were performed in order to compare the energy efficiency.

The value of input current and EVA current is measured by Hall effect LEM current sensors. Measurement of the output displacement of the LCE and detection of its passage through the equilibrium position is accomplished by a non-contact inductive displacement sensor operating in the displacement range ±5mm and frequency range 0-1kHz. The signal of this sensor is transmitted by an electronic amplifier and normalized to the 0-5V level. The instantaneous value and average value of EVA power is measured by watt sensor PI series, *F.W.Bell Company*, with ac and dc output, respectively.

V. The Experimental Results

This chapter will present the experimental results on which base the energy efficiency of phase control and switch mode RVCD were compared. This comparison was based on the same conditions that were established for the electrical and mechanical parts of the RVCD system.

The parameters of the mechanical part of the system and the electrical parameters of the EVA are given in Table I.

TABLE I. Mechanical and Electrical Parameters of RVCD

MECHANICAL PARAMETERS of CONVEYOR		
Mass of LCE without material	m_{k0} [kg]	1.15
Stiffness of flexible elements (fiberglass springs)	k [N/mm]	113.50
Equivalent damping koeficient of the system	β [N/m/s]	3.3-13.0
Change mass of LCE	Δm_k [kg]	0.306
ELECTRICAL PARAMETERS of EVA		
Inductance at equilibrium position	L_0 [H]	1.20
Resistance of coil	R_C [Ω]	100.00
Air gap in equilibrium position	D[mm]	6.00

A. *Experimental results for phase control RVCD*

Experimental results for the phase control SCR drive were carried out under the following conditions: mains voltage 380V, mains frequency 50Hz and range of phase angle changes 60°-170°.

Oscilloscopic records of LCE displacement and EVA current, at changing of mass LCE are shown in Figure 5. In intention to induce the sudden change in weight of LCE, in empty vibrating channel of LCE, 306g of used particulate material (white refined sugar) was thrown.

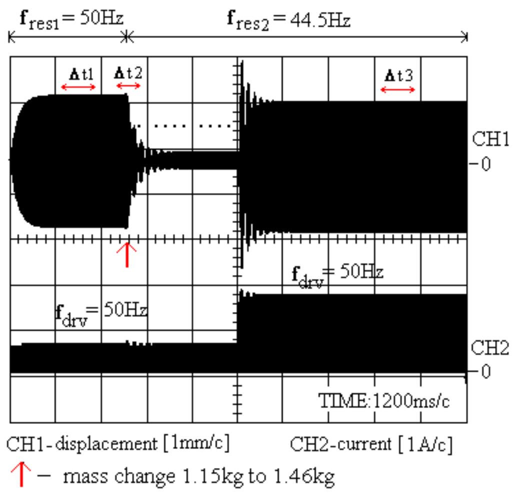

Figure 5. The compensation of mass change of LCE usiong phase control RVCD

To the moment marked with *arrow*-↑, LCE was empty and it vibrated with *peak to peak* amplitude $P_{p-p1} = 3mm$. Under these conditions, the mechanical resonance frequency of the system was $f_{res1} = 50Hz$ and it was equal to the driving frequency $f_{drv1} = 50Hz$ of the EVA (i.e. mains frequency 50Hz).

After a sudden change in mass of the vibrating channel, with an unchanged frequency and intensity of the EVA current excitation, there has been a considerable change in the amplitude of vibration from $P_{p-p1} = 3mm$ to $P_{p-p2} = 0.4mm$. After the change in mass of LCE, there has been a change in the mechanical resonant frequency from $f_{res1} = 50Hz$ to $f_{res2} = 44.5Hz$.

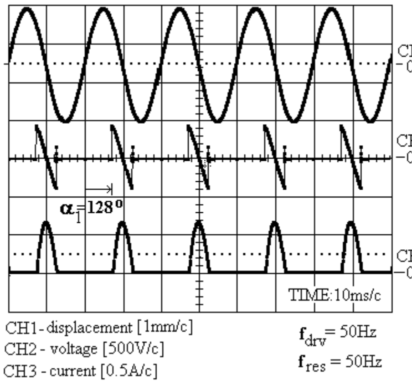

Figure 6. Detailed scope of time interval Δt1

In order to maintain constant vibration amplitude with the phase control SCR power converter, in case of this disturbance, it is only possible to achieve a change of phase angle.

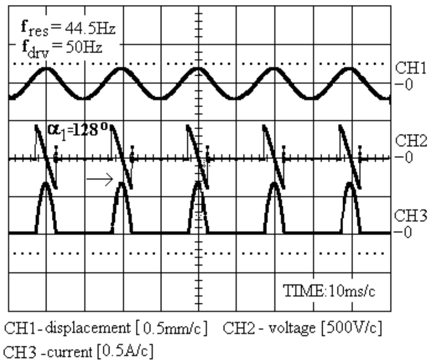

Figure 7. Detailed scope of time interval Δt2

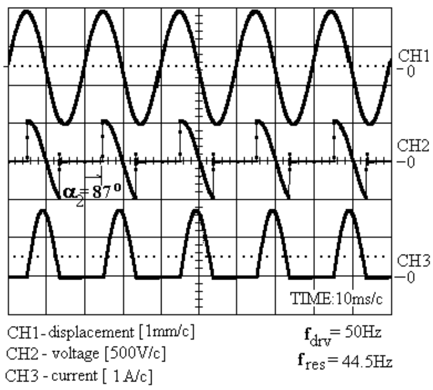

Figure 8. Detailed scope of time interval Δt3

Reducing the phase angle resulted in increased amplitude and duration of the EVA current, and compensation of disturbance. It is important to highlight, that it is not possible to change driving frequency, since it is determined by mains frequency (50Hz). Detailed view of the characteristic time intervals $\Delta t_1 - \Delta t_3$ of oscilloscopic records in Figure 5, are shown in Figures 6 -8.

Figure 9 shows the oscilloscopic records of mains voltage, input current, EVA voltage and instantaneous input power needed to maintain the vibration amplitude of LCE in time intervals Δt_1 and Δt_3.

In Figure 9 (a) time interval Δt_1 is shown in detail in which the phase angle was $\alpha_1 = 128^0$, while the amplitude of oscillation was $P_{p-p1} = 3mm$. In this case, the resonant mode is established, and the mean value of instantaneous input power i.e. active input power was about 6.5W, as shown in oscilloscopic records in Figure 9 (a).

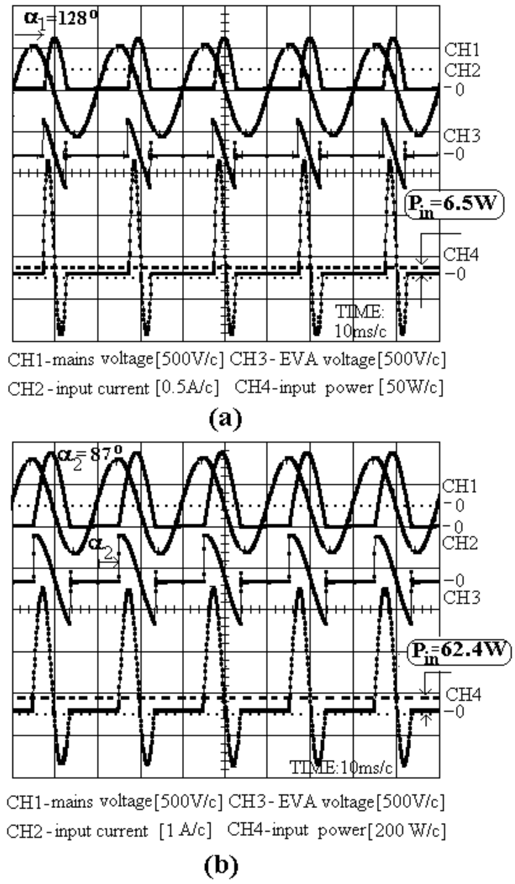

Figure 9. Oscillloscopic records of mains voltage, input current, EVA voltage and instantaneous input power; (a) time interval Δt1, phase angle α_1=128^0, (b) time interval Δt3, phase angle α_2=87^0

In Figure 9 (b) time interval Δt_3 is shown in detail in which the phase angle was $\alpha_2 = 87^0$, while the amplitude of oscillation at these conditions remained constant, and was also $P_{p-p3} = P_{p-p1} = 3mm$. In this interval, the resonance frequency of the system was reduced for $\Delta f = 5.5$ Hz because there was an increase of mass $\Delta m = 0.306kg$, due to the LCE vibratory trough filling of particulate material.

Maintaining the amplitude of oscillation can only be achieved by increasing the amplitude and time duration of the current EVA (i.e. decreasing phase angle to value $\alpha_2 = 87^0$, as shown in oscilloscopic record in Figure 9(b). The active power consumption in this case is much higher than in the resonant mode, and it was about 62.4W.

This experiment clearly shows how the resonant mode energy is efficient. The energy efficiency of the vibratory drive can be significantly increased in the new regime with lower resonant frequency using a frequency controlled switch mode power converters.

B. Experimental results for switch mode RVCD

Similarly as in previous case of phase control RVCD, typical responses were recorded during quick disturbance, for a case of switch mode RVCD. Oscilloscopic record is shown in Figure 10.

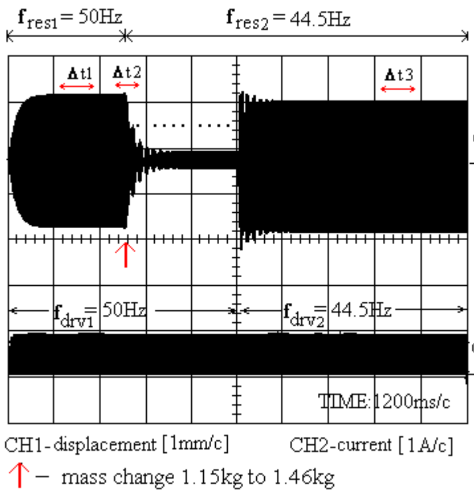

Figure 10. The change mass compensation of LCE using switch mode RVCD

The oscilloscopic records in Figure 10 show that the maintenance of amplitude of oscillations of LCE is achieved with unchanged amplitude of EVA current, but with change of its driving frequency f_{drv} (50Hz→44.5Hz).

In other words, the tracking of resonant frequency can maintain constant oscillation amplitude with very low power consumption.

Figure 11 shows the detailed oscilloscopic records of characteristic value (measured value of interest) in time interval Δt_1 : mains voltage, input current, EVA voltage, EVA current, LCE displacement, instantaneous EVA power and instantaneous input power needed to maintain the vibration amplitude of LCE.

In Figure 11(a) time interval Δt_1 is shown in detail, in which the pulse width of EVA current control signal was $\delta_1 = 9\%$, while the amplitude of oscillation was $P_{p-p1} = 3mm$. In this interval the driving frequency is equal to a resonant frequency i.e. $f_{drv1} = f_{res1} = 50Hz$.

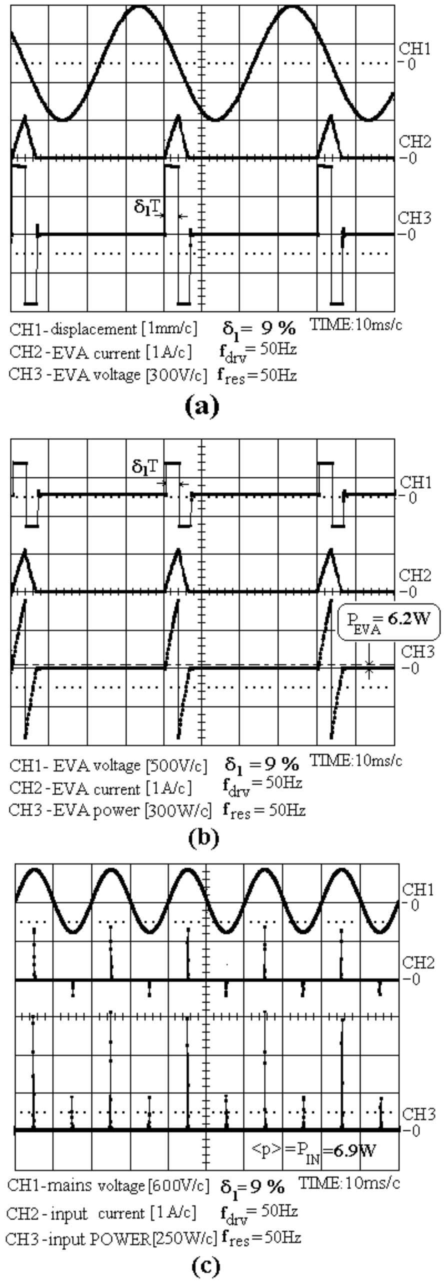

Figure 11. Detailed scope of interval Δt1 for switch mode RVCD; (a) oscilloscopic records of displacement of LCE, current and voltage of EVA, (b) oscilloscopic records of voltage , current and instantaneous power of EVA, (c) oscilloscopic records of input values: current, voltage and power

In this case, the resonant mode is established, and the mean value of instantaneous of EVA power i.e. active EVA power was about 6.2W, show as in oscilloscopic records in Figure 11(b).

In Figure 11(c) are shown oscilloscopic records of mains voltage, input current and instantaneous input power. The measured average input power (active power) was about 6.9W. The difference between the input and output EVA power is the result of total losses of energy conversion.

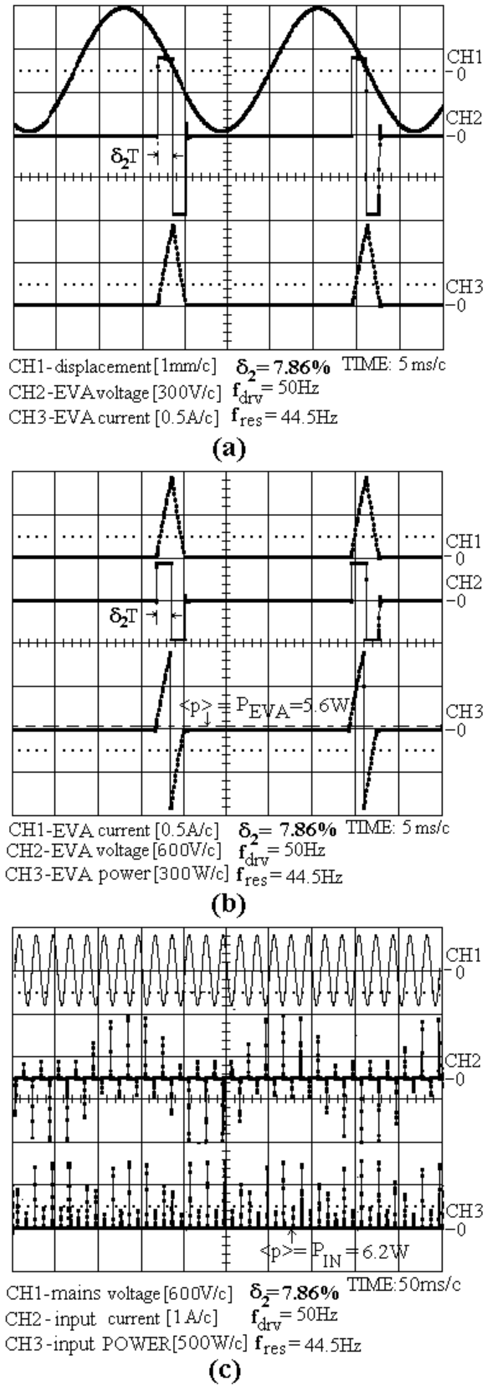

Figure 12. Detailed scope of interval Δt3 for switch mode RVCD; (a) oscilloscopic records of displacement of LCE, current and voltage of EVA, (b) oscillloscopic records of voltage , current and instantaneous power of EVA, (c) oscilloscopic records of input values:mains voltage, current and input power

In Figure 12 time interval Δt_3 is shown in detail in which the pulse width of EVA current control signal was $\delta_2 = 7.86\%$, while the amplitude of oscillation was on constant value $P_{p-p1} = 3mm$. In this interval the driving frequency is equal to a new resonant frequency i.e. $f_{drv2} = f_{res2} = 44.5Hz$.

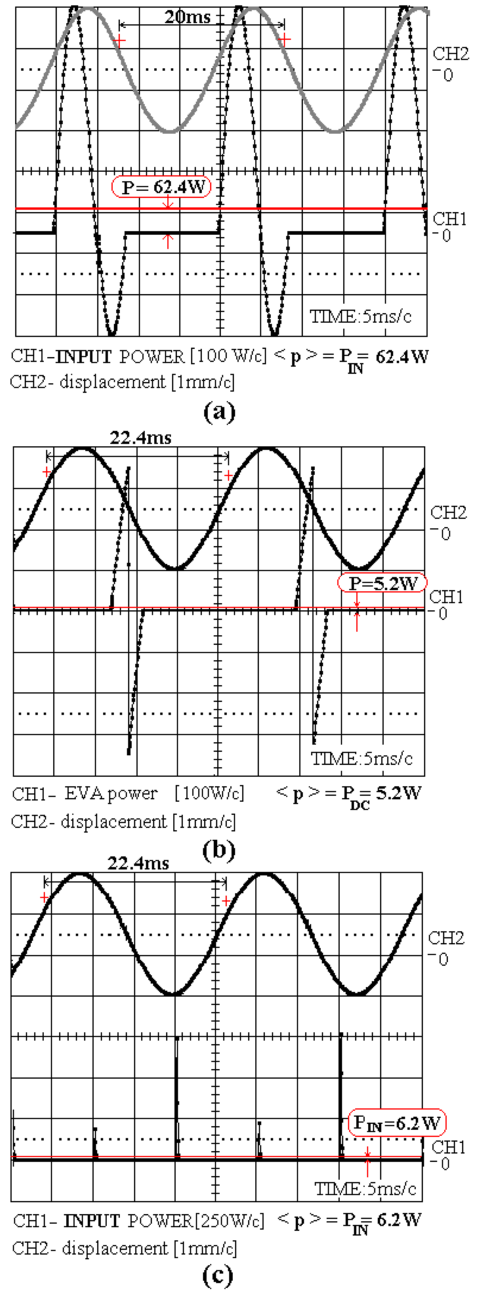

Figure 13. Oscilloscopic records of instantaneous of input power in a new resonant mode *fres=44.5Hz*; (a) phase control SCR power converter *fdrv=50Hz*, (b)EVA power-SMPC , *fdrv=44.5Hz*, (c) input power of switch mode power converter, *fdrv=44.5Hz*

In this case, the resonant mode is also established, and the average value of active EVA power is slightly less than the interval Δt_1, as can be seen in oscilloscopic records in Figure 12 (b).

In a new resonant regime (interval Δt_3) vibration amplitude was $P_{p-p2} = 3mm$, while the driving frequency of EVA is aligned with the new resonant frequency i.e. $f_{drv2} = f_{res2} = 44.5Hz$. Under these conditions, the EVA power consumption was 5.6W.

In Figure 12(c) are shown oscilloscopic records of mains power, input current and instantaneous input power consumption of switch mode RVCD. The measured average input power was about 6.2W.

At the end of the experimental results presentation, oscilloscopic records of the instantaneous EVA power, instantaneous input power in the case of phase control and switch mode RVCD, are given in Figure 13. In that case conditions were the same, that is, the vibratory trough of LCE was loaded with 306g of particulate material (white refined sugar).

Figure 13 (a) shows the instantaneous value of the input power in the new resonant mode ($f_{res2} = 44.5Hz$ and $f_{drv2} = 50Hz$) for case of phase control RVCD. The average value of the power for this mode was 62.4W, while the amplitude of the LCE oscillations was $P_{p-p2} = 3mm$.

Figure 13 (b) shows the instantaneous value of the EVA power in the new tracking resonant mode ($f_{res2} = 44.5Hz$ and $f_{drv2} = 44.5Hz$), in case of switch mode RVCD. The average value of the EVA power for this mode was 5.2W, while the amplitude of the LCE oscillations was $P_{p-p2} = 3mm$.

Figure 13(c) shows the instantaneous value of input power of switch mode RVCD in a new resonant mode. The mean value of the input power for this mode was 6.2W, while the amplitude of the LCE oscillations was, as in previous case i.e. $P_{p-p2} = 3mm$.

From the previous results it can be seen that for maintenance of the constant LCE oscillation amplitude i.e. gravimetric flow of particulate material, in a new resonant regime (resonant frequency $f_{drv2} = 44.5Hz$), significantly less input power is required in the case of switch mode RVCD, compared to phase control RVCD. In that way, the energy efficiency of this drives has been proven and their use in the particulate material processing industry (conveying, dosing, compacting etc.) is justified.

VI. Conclusions

The request for optimum operation of RVCD in resonant range persists in modern industrial and technological processes: conveying, processing and dosing of bulk materials.

The research presented in this paper has shown that it is possible to achieve significant energy efficiency of RVCD, by using switching power converter for amplitude and frequency control of the vibratory conveying.

In this paper a comparison of practically realized conventional phase control SCR and switch mode IGBT power converter used for RVCD and experimental results from the stand point of energy efficiency, were presented.

The experimental results presented in this paper shown that the resonant mode of vibration conveyor with electromagnetic excitation is very advantageous, since then it consumes the least energy to maintain the system in a state of oscillation.

It was noted that the algorithm of tracking mechanical resonant frequency, that was implemented in switch mode RVCD, can achieve power savings of up to ten times in relation to a phase control RVCD. This has a great importance in process systems containing a number of these vibratory conveying drives.

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