15th INTERNATIONAL SYMPOSIUM on
POWER ELECTRONICS - Ee 2009
XV Međunarodni simpozijum Energetska elektronika – Ee 2009
NOVI SAD, REPUBLIC OF SERBIA, October 28th - 30th, 2009

LOW FREQUENCY IGBT CONVERTER FOR CONTROL EXCITING FORCE OF ELECTROMAGNETIC VIBRATORY CONVEYORS

Željko Despotović, Aleksandar Ribić
Mihajlo Pupin Institute, Belgrade, Republic of Serbia, zeljko@robot.imp.bg.ac.rs

Abstract: *The resonant electromagnetic vibratory conveying drives (EVCD) are often used to control of the gravimetric flow and dosing of particulate material. The realization of vibration with variable intensity and frequency in a wide range is achieved by means of suitable power converter and corresponding controller. The range of amplitude oscillation for most EVCD is 0.1mm-100mm, while the frequency range is 1Hz-100Hz. Today, as the standard output power stages are used thyristors and triacs. Their use implies the phase angle control (PAC). Since the power supply network is fixed frequency, with PAC is only possible to adjust amplitude oscillations of EVCD but not their frequency. With transistor power converter it is possible to achieve sinusoidal or triangular half-wave current of actuator and setting his force. The application of sinusoidal wave includes the current control with a relatively high switching frequency, while the generation of triangular wave is based on the programmed current control at lower frequency. This second method has the significant advantage, since the power losses in the converter are significantly lower. In addition, to adjusting amplitude and time duration of the exciting force provide its frequency control. In this way, operation of EVCD becomes independent of network supply frequency. The paper presented a possible solution low-frequency IGBT switching converter for excitation force control of resonant EVCD.*

Key Words: ***Vibratory conveyor, vibratory actuator, current control, force control, power converte, IGBT***

1. INTRODUCTION

The vibratory conveyors are widely used device in various technological processes for transporting and finishing materials. Conveying process is based on a sequential throw movement of particles. Vibrations of tank, i.e. of a *"load-carrying element"* (LCE), in which the material is placed, induces the movement of material particles, so that they resemble to a highly viscous liquid and the material becomes easier for conveying. In the processing industry are often used mechanisms based on the vibratory conveyors with electromagnetic drive. Vibratory conveying drives with electromagnetic vibratory actuator (EVA) are a very popular because of their high efficiency and easy maintenance [1], [2].

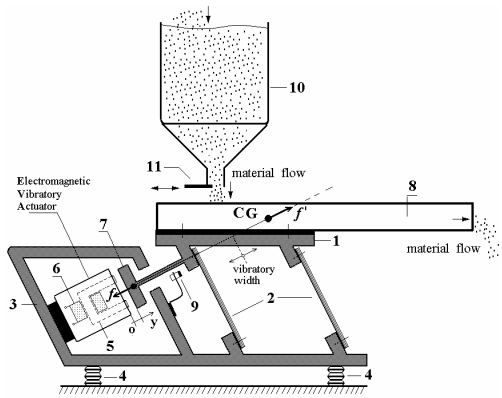

Fig.1. *Typical construction of vibratory conveyer with electromagnetic drive*

A typical arrangement of electromagnetic vibratory conveying drive (EVCD) can be seen in Fig.1. Its main components are *LCE*-1, EVA as source of excitation force and *flexible elements*-2. Flexible elements are made of composite leaf springs. These elements are rigidly connected to the *base*-3, which is resting on *rubber pads*-4 to the foundation. *Magnetic core*-5 is covered by continuous *winding coils*- 6. Electromagnetic force f acts on *armature*-7 attached to the LCE. This element carries the *vibratory trough*-8 along with transporting material. The vibratory displacement is measured by non-contact *inductive sensor*- 9**.** The granular material comes to the trough from *storage hopper*- 10. Input flow is adjusted by *movable shutter*- 11.

Application of electromagnetic vibratory drive in combination with power converter provides flexibility during work. It is possible to provide operation of the vibratory drive in the region of the mechanical resonance. Resonance is highly efficient, because large output displacement is provided by small input power. In this way, the whole conveying system has a behavior of the controllable mechanical oscillator [3], [4].

SCR converters are used for the EVA standard power output stage. Their usage implies a phase angle

control [4-6]. Firing angle varying provides the controlled AC or DC injection current of EVA or controls his mechanical force. This force is squared function of current in EVA winding coils [3], [5-7].

One type of this converter-*unidirectional,* with DC pulsing output current, using only one half period of mains voltage. They are implemented with a one thyristor as shown in Fig.2 (a). In this case thyristor firing is achieved only in positive half wave as shown in Fig.3 (a). The output voltage (50Hz or 60Hz) is converted to pulsating DC current of EVA i.e. pulsating force of EVCD. In this way, generate vibrations of discrete spectrum like in Fig.3, depending on the moment of thyristor firing.

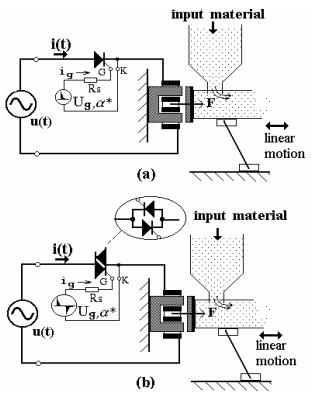

Fig.2. *Power converter with phase angle control for vibratory conveying control; (a)-unidirectional, (b)-bidirectional*

Another type power converter- *bidirectional* with AC output current, using full period of mains voltage. They are implemented with triacs or ant-parallel connection of thyristor for higher power application, as shown in Fig.2 (b).With these power converters is the mains frequency 50Hz/60Hz converted to AC power supplied to the same frequency coil EVA as shown in Fig.3(b).

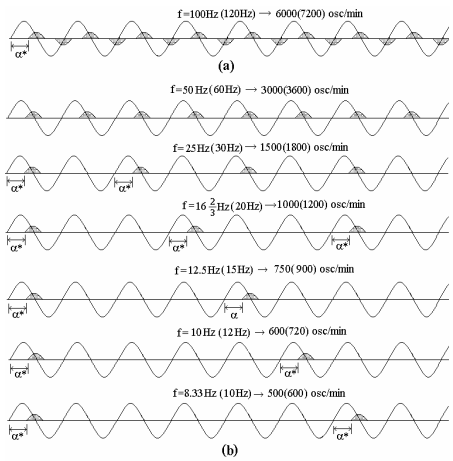

Fig.3. *PAC for vibratory conveying drive; EVA voltage and current; (a)-bidirectional mode, (b)-unidirectional mode*

Today is intensively working on implemented of high-frequency (HF) power converters for obtaining sinusoidal current in the EVA. As in the case of SCR can talk about on unidirectional and bidirectional converter type, depending on whether there was DC pulsating or AC excitation of EVA. The generally accepted topologies are shown in Fig.4.

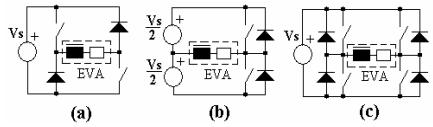

Fig.4. *Power converter switching topology for driving EVA; (a)- asymmetrical half bridge,(b)-symmetrical half bridge, (c)-full bridge*

The HF switching converters, despite significant merits, have a shortcoming of having switching losses which become dominant at high frequencies. This reduces the efficiency of the EVCD and power losses in the converter are often higher than the power required for maintaining the resonant oscillatory regime. This reduces considerably the efficiency of the whole system [9].

By suitable way to control of EVCD it is possible to overcome this problem. In the present paper this is obtained by generating low frequency triangle current pulses of EVA. One possibility is to use half-bridge like in Fig.4 (a).

2. MODELLING OF *EVCD* DYNAMICS

Principle of amplitude-frequency control means actuating force is given on the block diagram in Fig.5. A high performance exciting force control of EVCD requires a detailed analysis of their electromagnetic and mechanical part.

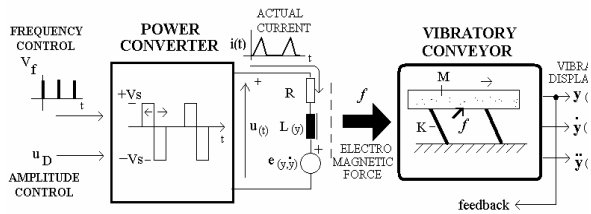

Fig.5. *Principal block diagram of regulated EVCD*

2.1-Electromagnetic part

Detailed electrical model of EVA is derived in [5]. It can be written as [10-13]:

$$L(y)\frac{di}{dt}+\left(\frac{\partial L(y)}{\partial y}\frac{dy}{dt}+R\right)i=u \qquad (1)$$

$$f=\frac{1}{2}\frac{\partial L(y)}{\partial y}i^2 \qquad (2)$$

where, R and $L(y)$ denotes EVA coil electrical resistance and inductivity, and y, i, u denotes LCE position in relation to conveyer base, EVA coil current and EVA coil voltage respectively. Mechanical force f is produced by the electromagnet. According to Fig.5, EVA coil voltage u depends on control voltage u_D:

$$u=\begin{cases} V_s, u_D=1\wedge\Delta i>0 \\ -V_s, u_D=0\wedge\Delta i<0 \\ 0, u_D=0\wedge i=0 \end{cases} \qquad (3)$$

where V_s is source voltage. As will be shown later, pulses are always triggered around equilibrium position $y=y_0$, so L(y) could be approximated

with $L(y) \approx L_0 + (y - y_0) \cdot \partial L / \partial y \big|_{y=y_0}$. Now, equation (1) can be approximated around $y = y_0$ as:

$$L_0 \frac{di}{dt} + R'i = u, R' = R + \frac{dy}{dt}\frac{\partial L}{\partial y}\bigg|_{y=y_0} \quad (4)$$

where parameter R' , dependant on velocity *dy/dt* , represents equivalent resistance. Pulses generated by control logic are short, so supposing that the equivalent time constant L_0 / R' is much greater then pulse duration, we obtain $R'i << u$. Now, we can neglect term $R'i$ in (4), so final approximation of (1) is given by:

$$\frac{di}{dt} = \frac{u}{L_0} \quad (5)$$

2.2 Mechanical part

Detailed mechanical dynamics model of EVCD is given in [10-14] and has the following form:

$$M\ddot{z} + C\dot{z} + Kz = \Gamma f \quad (6)$$

Vector $z \in R^4$ represents state vector containing positions and angles of respective parts, and *M*, *C*, and K are symmetric matrices. Vector Γ defines acting of force f onto the corresponding parts [4-6], [10], [15]. The equation (5) implies four oscillation modes of the given system, but not all of them are interesting for analysis. Particularly, all machines are mechanically constructed in the manner that undesirable modes are highly damped and/or excited in the smallest possible measure. This fact leads to conclusion that model of the mechanical part of EVCD can be approximated with only one dominant oscillating mode [4-6], [11-13], [15] :

$$\ddot{y} + 2\varsigma\omega_0 \cdot \dot{y} + \omega_0^2 \cdot (y - y_0) = K_p \cdot \omega_0^2 \cdot f \quad (7)$$

where ω_o (rad/s), ς and K_p denotes resonant frequency, damping factor, and static gain respectively.

3. CURRENT CONTROL of *EVA*

The simple pulse width control, applying to the topology in Fig. 4(a), provides easy and simple control of EVA coil current. Control circuit wheel that provides the amplitude, duration and frequency adjust of triangle current half-wave is shown in Fig.6. With the appropriate sensors is measured the value of the *EVA current* $-i(t)$. Measured signal is amplified with K_i value and thus enhanced signal is introduced into the adder where it is compared with the reference value of amplitude current I_{Mref}. Setting of RS flip-flop (FF) is realized from the impulse voltage controlled oscillator (VCO). This oscillator determines the frequency i.e. the period T_d of triangle half- wave current.

Bringing the signal from the VCO on the set input of the FF establishes the state of logical "1" at its output Q . In this case switches Q1 and Q2 are in the state "ON". This establishes a current through the EVA coil in rising ramp as a positive voltage $+V_s$ is applied to the EVA coil, as shown in Fig.6 (b). This increase is realized until the moment when the actual value of the current- $i(t)$ reaches a reference value of amplitude I_{Mref} , when the reset pulse is generated at the input R to the FF.

After that comes to establishing state logical "0" on its Q output. In this case switches Q1 and Q2 are in the state "OFF", while the EVA coil current takes free-wheeling diode D1 and D2. Accordingly it is obtained a linear decrease of EVA coil current, since the negative voltage -Vs applied to it. This reset state is retained until the appearance of a new set impulse from the VCO.

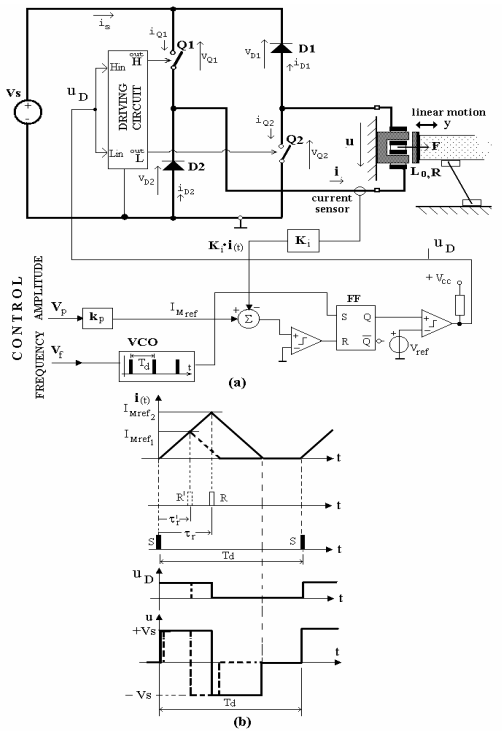

Fig.6.*Programming current control for adjusting amplitude, duration and frequency of EVA coil current; (a)-principal sheme , (b)-characteristics waveforms*

The amplitude and time duration of EVA coil current are determined by control voltage V_p, which actually represents the value of I_{Mref}. The frequency of current pulses i.e. excitation force pulses is determined by control voltage V_f .

Since the reactive resistance of the EVA coil is dominant (much higher than the active resistance) can write the approximately relation for *rising time* τ_r of EVA current:

$$\tau_r \approx \tau_f = \frac{L_0 \cdot I_{Mref}}{V_s} \quad (8)$$

and relation for total duration of the EVA current :

$$\tau \approx \frac{2 \cdot L_0 \cdot I_{Mref}}{V_s} \quad (9)$$

From these relations it follows important conclusion that the duration of the current half-wave is linear function of I_{Mref} .

4. SIMULATION RESULTS

The characteristic waveforms in the case of the previosly described current control are given in this

section.The influence of current reference changes and control logic signals at the entrance to the FF on the EVA current and output displacement are given in Fig.7.

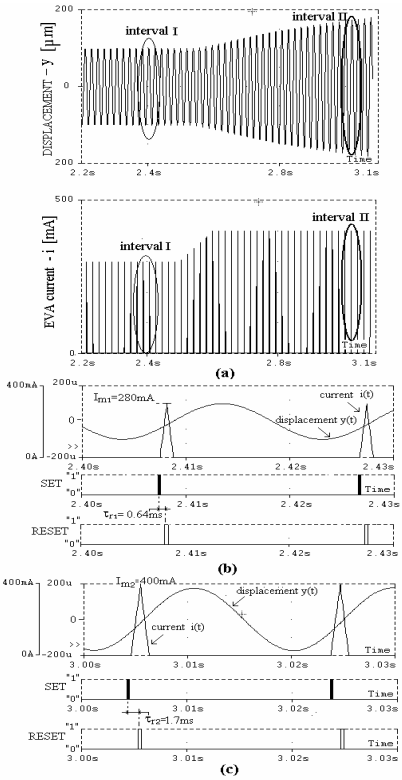

Fig.7. *The influence of refrence current change on the output displacement of EVCD; (a)-output displacement and EVA current, (b)-detail of interval I , (c)-detail of interval II*

In the simulation is set to the value of the resonant frequency of the mechanical system f_{rez}=52Hz and period of driving pulses T_d=19.3ms (f_{pob}=52Hz).

The simulations records of vibratory trough displacement- $y(t)$ and EVA current- $i(t)$ in the case of changing amplitude current reference are given on Fig.7 (a). On the simulation records are marked two intervals of interest.

These intervals are presented in detailed together with the corresponding control signals SET and RESET. The *interval-I* is given on the Fig.7 (a), while the *interval-II* is given on the Fig.7(c). In the first moment is established stationary regime with amplitude displacement value of Y_{m1}=0.1mm i.e. vibratory width value of $Y_{(p-p)1}$=0.2mm in which the amplitude of EVA current was I_{m1}=280mA .In the moment of time t=2.5s is setting sudden increase of reference value of current half-wave forms around 40%. As a result, there has been an increase in amplitude of the output displacement on the value Y_{m2}=0.2mm i.e. vibratory width value of $Y_{(p-p)1}$=0.4mm . In addition to the current amplitude changes has been a change of time increase the value of EVA current from value τ_{r1}=0.64ms to value τ_{r1}=1.70ms .These values actually represent the time interval between corresponding pulses SET and RESET of FF, as shown in Fig.7(b),(c).

5. EXPERIMENTAL RESULTS

The experimental results are obtained on real realized laboratory prototype of resonant EVCD at which the applied current control and high performance exciting force control. The principle scheme of the realized system with IGBT power converter is given in Fig.10. Detailed description of this IGBT converter is given in [3]. It is experimentally observed the values of interest: *EVA current- i(t)* and *output displacement of vibratory trough – y(t)*.

On the oscilloscopic records in Fig.8. are shown the impact of changes in the duration of current pulse on the output displacement of vibratory trough at the resonant frequency f_{rez}=45.5Hz and unchanged amplitude current I_{Mref}=0.5A . At the stationary and unchanged resonance regime, change of current pulse duration for about 33%, caused a nearly twofold greater change in the value of the amplitude oscillation of the vibratory trough.

On the Fig.9 are shown the load change compensation of EVCD and oscilloscopic records of characteristic values (EVA current, EVA voltage and displacement of vibratory trough).

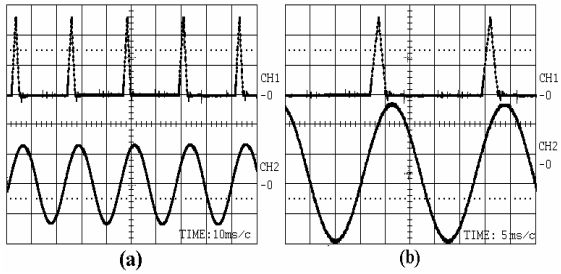

Fig.8. *The influence of change EVA current duration on the output displacement;(a)-EVA current duration τ=3ms,(b)- EVA current duration τ=4ms; CH1- EVA current (0.2A/c),CH2- displacement (1mm/c).*

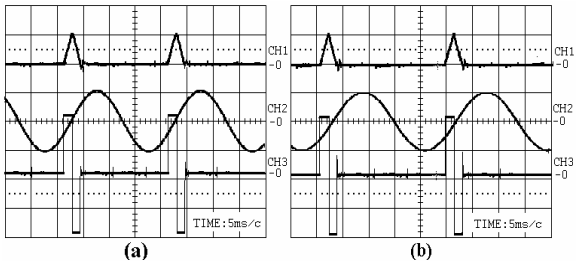

Fig.9. *The load mass compensation of EVCD through changing frequency of EVA current, (a)-excitation frequency* $f_{p1}=f_{rez1}$=50Hz *(b)- excitation frequency* $f_{p2}=f_{rez2}$=41.5Hz *; CH1-EVA current (0.5A/c),CH2- displacement (2mm/c), CH3-EVA voltage (200V/c).*

The mass change was achieved with from m_{k0}=1.15kg to value $m_{k1} = 1.65kg$. Oscilloscopic records for mass load m_{k0} (empty vibratory trough) are shown on Fig.9 (a). Oscilloscopic records for mass load m_{k1} are shown on Fig.9 (b). The load change compensation and maintaining constant vibration amplitude of vibratory trough is achieved by changing the frequency of EVA current (from f_{rez1}=50Hz to f_{rez2}=41.5Hz) at same value of time duration τ=4ms .

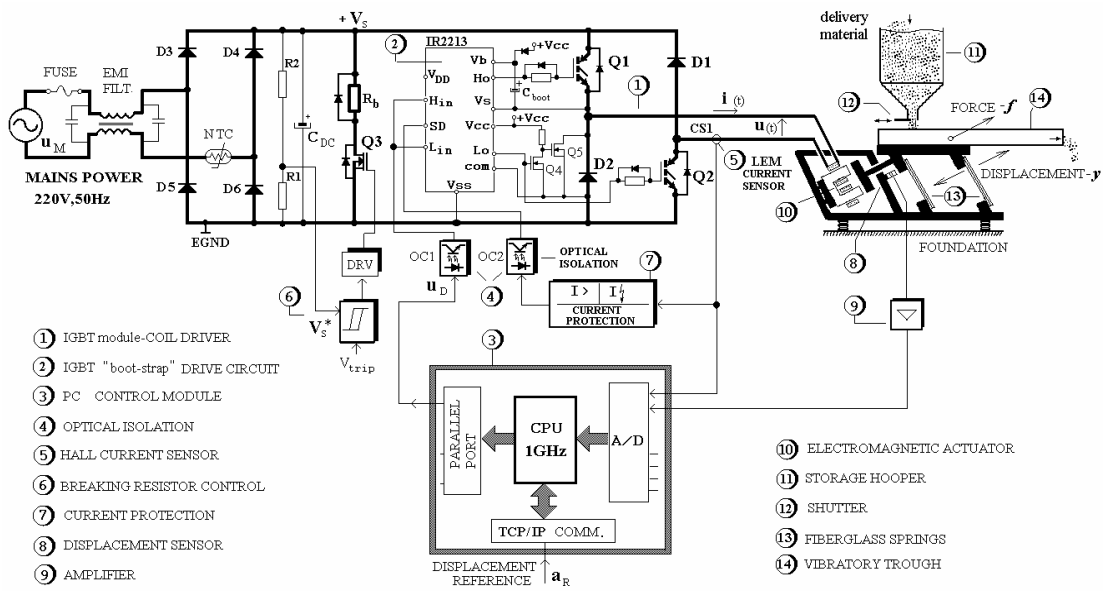

Fig.10. *Principal diagram of implemented IGBT converter for current control of EVCD*

The mass change was achieved with from m_{k0}=1.15kg to value $m_{k1} = 1.65kg$. Oscilloscopic records for mass load m_{k0} (empty vibratory trough) are shown on Fig.9 (a). Oscilloscopic records for mass load m_{k1} are shown on Fig.9 (b). The load change compensation and maintaining constant vibration amplitude of vibratory trough is achieved by changing the frequency of EVA current (from f_{rez1}=50Hz to f_{rez2}=41.5Hz) at same value of time duration τ=4ms .

6. CONCLUSION

The paper presented a possible solution to excitation force control of EVCD. Presented simulation and experimental results showed that current control of EVA is a very effective way to amplitude and frequency control of resonant EVCD. Resonant regime is very important from the aspect of minimizing energy consumption of the entire EVCD.

The current control is achieved such that a mechanical system is controllable mechanical oscillator, independent of the supply network frequency, which was achieved a significant improvement compared to the thyristors and triacs drives.

7. REFERENCES

[1] H.G.Cock ,*"Vibratory Feeders"*-PHILIPS Technical Review, Vol.24, May 1975,pp.84-95.

[2] P.U.Frei, "An Intelligent Vibratory Conveyor for the Individual Object Transportation in Two Dimensions", *Proceedings of the 2002 IEEE/RSJ, Intl. Conference on Intelligent Robots and Systems*, EPFL, Lausanne, Switzerland, October 2002, pp.1832-1837.

[3] Z.Despotovic and Z.Stojiljkovic, "Power Converter Control Circuits for Two-Mass Vibratory Conveying System with Electromagnetic Drive: Simulations and Experimental Results", *IEEE Transaction on Industrial Electronics,* Vol.54, Issue I, Februar 2007,pp.453-466.

[4] T.Doi, K.Yoshida, Y.Tamai, K.Kono, K.Naito, T.Ono, *"Modeling and Feedback Control for Vibratory Feeder of Electromagnetic Type",* Journal of Robotics and Mechatronics , Vol.11, No.5, June 1999, pp. 563-572.

[5] N.Barjamović,"Tiristori u sistemima za doziranje rasutih materijala", *II simpozijum Energetska elektronika – Ee '75,* Beograd (YU), Oktobar 1975, pp.334-348.

[6] T.Doi, K.Yoshida, Y.Tamai, K.Kono, K.Naito, T.Ono, *"Feedback Control for Electromagnetic Vibration Feeder",* JSME International Journal, Series C, Vol.44, No.1, 2001, pp. 44-52.

[7] Ž.Despotović, M.Jovanović, Z.Stojiljković, "Tiristorski pretvarač za pogon elektromagnetnih vibratora", *X simpozijum Energetska elektronika – Ee '99,* N.Sad (YU), Oktobar 1999, pp.150-156.

[8] Z.Despotovic, Z. and Z. Stojiljkovic, "PSPICE Simulation of Two Mass Vibratory Conveying System with Electromagnetic Drive" , *PROCEEDINGS of International Conference EUROCON 2009-"Computer as a tool"* , Belgrade 21.XI.-24.XI.2005, Vol. II, pp.1509-1512.

[9] Z.Despotovic, Z.Stojiljkovic, "*A Realization AC/DC Transistor Power Converter for Driving Electromagnetic Vibratory Conveyors*", PROCEEDINGS of the V Symposium of Industrial Electronics-INDEL, Banja Luka, 11-13.IX.2004, Vol. T2A, pp.34-40.

[10] V.Gourishankar, D.H.Kelly, *"Electromehanical energy conversion",* Billing and Sons Ltd., Guldford & London, London, 1973.

[11] Z.Despotovic,"*Mathematical model of electromagnetic vibratory actuator*", PROCEEDINGS of the XII International Symposium of the Power Electronics, N.Sad 5.XI-7.XI.2003, Vol.T3-3.2, pp.1-5(In Serbian).

[12] S.Seely, *Electromechanical energy conversion",* McGraw-HILL Book Company INC., New York, 1962.

[13] Z.Despotovic, M.Pesko, "*Mathematical Model of Vibratory Feeder Drive with Electromagnetic Vibratory Actuator*", PROCEEDINGS of the XLVIII Conference ETRAN, Cacak, 8-13.06.2004, Vol.I, pp.276-279.

[14] P.Wolfsteiner, F.Pfeiffer, *"Dynamics of a vibratory feeder",* PROCEEDINGS of DETC '97, ASME Design Engineering Technical Conferences, Sacramento, California, DETC97/VIB-3905,Sept.14-17,1997, pp.1-9.

[15] T.Doi, K.Yoshida, Y.Tamai, K.Kono, K.Naito,T. Ono "Feedback Control for Vibratory Feeder of Electromagnetic Type", *Proc. ICAM'98*, 1998, pp. 849-854.