DC injection in low voltage power network produced by regulated resonant vibratory conveying drives

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Abstract— **Electromagnetic resonant vibratory conveying drives (VCD) are often used to control the gravimetric flow of particulate materials. Their operations are based on resonance phenomena. Resonance is highly efficient, because large output displacement is provided by small input driving current. The realization of vibration, variable intensity and frequency is achieved by means of suitable power converters (SCR or Switch Mode) and the corresponding controller. In this way, the whole conveying system has behavior of a controllable mechanical oscillator. Despite the significant advantages offered by these regulated drives, a problem imposes unidirectional current i.e. direct current (DC) component that they inject into the low voltage power supply network. It is especially great impact, if there is more regulated resonant vibration unit in operation. This is actually the most common case in practice, which occurs in industrial process systems (food, cement, pharmaceuticals, etc.). The DC component that can be injected into the power supply network can significantly distort the power quality of the other consumers. This paper presents the most unfavorable conditions under which may appear input DC component in these regulated drives and means and methods for its removal. Also, the paper will be presented simulation and experimental results concerning the study of DC injection current, as well as practically realized active electronic circuitry for its eliminating.**

Keywords-Power quality, DC injection, resonance, vibratory conveyor, SCR, IGBT, power converter, switch mode, regulated vibratory conveying drive, synchronisation, PFC.

I. INTRODUCTION

Resonant vibratory conveyors having electromagnetic drive are often used to control the gravimetric flow of bulk and particulate materials. This is useful method for conveying and processing materials in various pharmaceutics and food industrial process (drying, classification, dosing, compaction, granulation, dewatering etc...). Vibrations of a *"load-carrying element"* (LCE), in which the material is placed, induces the movement of material particles. LCE is in fact vibrating trough, usually of rectangular or trapezoidal cross-section. The material may be partially or completely fulfilled this trough. Conveying process is based on sequential throw of particles. In this case material resembles a highly viscous liquid and becomes easier for conveying and processing [1-5]. Also, it is possible to provide the operation of a conveying drive in the region of mechanical resonance. Resonance is highly efficient, because much of the output displacement of LCE is provided by little input power. The usage of an adequate power controller provides a continuous flow of material under different conditions. This is possible due to vibrations of variable intensity and frequency over a wide range.

Standard power stages intended for control of vibratory conveyance using SCR imply the use of phase angle control as shown in Fig.1. Phase angle variation can only accomplish tuning the amplitude of LCE oscillations, but not their frequency.

One type of these converters realized by using only one thyristor, i.e. *unidirectional* converters (Fig1(a)) which characterized by a pulsating output current, makes use of only one half-period of the network voltage. In this type of converter the thyristor is triggered only during positive half-periods. In this way the network voltage of frequency 50(60) Hz at the input is converted to a pulsating DC half waves. The current half-wave, which may have the frequencies 50(60)Hz, 25(30)Hz, 16.66(20)Hz, 12.5(15)Hz, 10(12)Hz, 8.33(10) Hz,..., supplying the electromagnetic actuator (actuating coil), which generates a discrete spectrum of vibrations respectively : 3000 (3600) cycles/min, 1500(1800) cycles/min, 1000(1200) cycles/min, 750(900) cycles/min, 600(720) cycles/min, 500(600) cycles/min,..., depending upon the instant of triggering of the thyristor [6-7]. Spectrum of the input current, in addition to a DC component, contains both lower and higher harmonics relative to the main component of 50Hz. The spectral composition of input current in this case is given in [7] and it's very dependent on the spectrum of vibrations. SCR converter brings in a DC component and undesirable higher harmonics. DC injection in power network is substantially determined by the instant triggering of thyristor i.e. by phase angle. The influence of such regulated vibratory conveying drives on the mains power network is strongly unfavorable and may lead to adverse effects.

The other type of converters i.e. bidirectional having an alternating output current (Fig1 (b)), make use of both half-periods of the network voltage. They are designed by using either triacs or anti-parallel connection of thyristors. For these converters the network voltage frequency 50(60) Hz is converted to an alternating current of the same frequency supplying the actuating electromagnet coil. Since the driving force of electromagnet vibratory actuator a square function of the coil current [6], [8-10] the driving force frequency is

100(120) Hz generating vibrations of 6000(7200) cycles/min [6-7]. In this case the spectral composition of the input current is favorable. DC injection is completely avoided, but the higher harmonics are significantly lower. However, despite the favorable harmonic composition, this topology has a number of disadvantages.

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. 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 a reduction of efficiency of VCD. In order to accomplish an optimal and efficient operation at a new resonant frequency, it is necessary to change the frequency of drive current, i.e. of the excitation force of the vibratory conveyor.

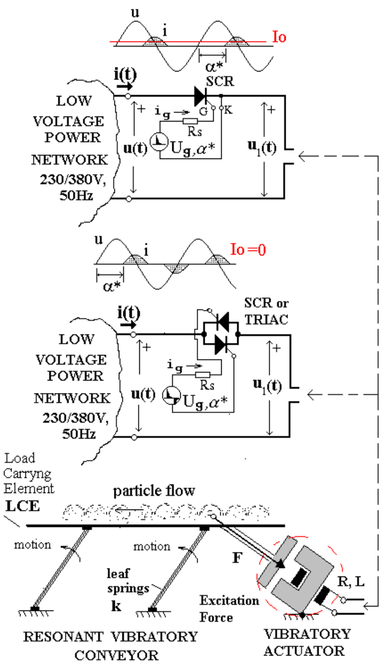

Figure 1. Influence SCR regulated vibratory conveying drives on the low voltage power network

Application of switch mode power converters (SMPC) enables accomplishing the amplitude and/or frequency control of a VCD [11-14]. The use of SMPC makes the excitation of a resonant VCD independent of the supply network frequency. The frequency control ensures operation of a VCD in the region of mechanical resonance. Despite many advantages, switch mode regulated VCD having electromagnetic drive under certain conditions can have injected DC in low voltage power network , especially if one takes into account the work of the resonant frequency which is close or equal to the network frequency.

II. Simulation Circuit for Examination of the Impact Regulated VCD to DC Injection

The regulation of amplitude oscillations and tracking the resonant frequency of the VCD is possible using switching converter topologies. Electromagnetic vibratory is possible to excite with triangular or sine half-wave currents and thus realize the impulse of driving force acting on the LCE. This ensures the topology which is detailed described in the references [6],[13]. All these topologies despite numerous advantages for the control of vibratory conveying, are very unfavorable consumer for the power network. In the references [7],[15] is exposed its influence on the low voltage power network , as regards the higher harmonic i.e. high frequency AC injection. However, under certain conditions this drives inject DC into low voltage power supply network. Especially it is the great impact, if there are more regulated resonant vibration units in operation.

The spectral composition of the input current for the case of a switching regulated VCD can be studied by simulation circuit of SMPS converter topology shown in Fig.2. The input converter is in fact a diode rectifier with a connection to the power supply network. At the output of the rectifier a current controlled asymmetric half-bridge is used to drive actuating coil of VCD. The operation of the output converter is described in detail in [6].[11],[14].

In this paper, the focus of the research will be made to examine the effect of VCD, but in terms of generating undesirable DC component of current that can be injected into the mains. The synchronization of current pulses i_{out} with the moments in which LCE passes through equilibrium position (displacement is equal zero), establishes a regime of mechanical resonance [9-13].

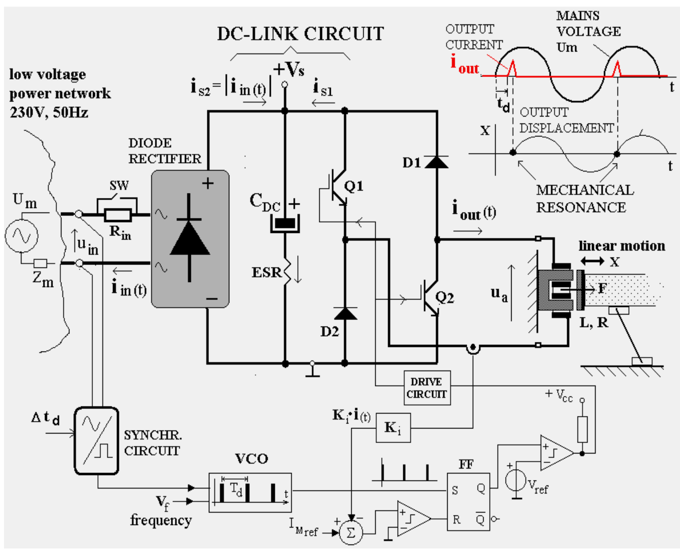

Figure 2. Simulation circuits for generation DC injection of regulated VCD

In this case, the output power stage compensates only the most dominant losses in the coil of actuating electromagnet and losses due to mechanical friction in mechanical part of VCD.

For the most of mechanical systems used in vibratory conveying, resonance frequency of the mechanical part of the system is in the range 5Hz-150Hz. The most of VCD's achieves oscillating operation at frequencies equal or very near to the network frequency 50Hz (60Hz). As regard the generation of DC component, the most unfavorable case is when the frequency of actuator excitation current VCD is equal to the power network frequency 50Hz. This case is the most critical and gives the most unfavorable spectral composition of the input current of VCD, which among other things contains a DC component.

It can be shown, that the excitation of the mechanical system corresponding to its resonant frequency of 50 Hz (the frequency of the excitation current of the actuator is also 50Hz), obtained qualitatively different forms of network input current (DC Injection), and depending on the moment when the generated impulse excitation force. For this purpose several simulations is performed on the circuit shown in Fig. 2.

In the simulations was varied phase shift, i.e. time interval between the moment of voltage network supply zero crossing (ZC) and moment, when it generates SET impulse to flip-flop in the control circuit VCD. SET impulse determines the moment when it starts to generate a pulsed excitation current actuator of VCD.

The obtained simulation results will be given in the next section.

III. SIMULATION RESULTS

This section presents the simulation results obtained to the previously described simulation round. Shows a few typical cases in which regulated VCD can generate DC current component in network terminals.

Values of the parameters used in simulation correspond to the case of a real VCD. These values are given in Table I.

TABLE I. PARAMETERS OF SIMULATION CIRCUITS

$V_S[V]$	$C_{DC}[\mu F]$	$ESR[\Omega]$	$L[mH]$	$R[\Omega]$
320	470	0.01	500	50

Fig. 3 shows the simulation results when SET impulse, which generates the excitation output current, leading to time td = 2ms, in relation to the moment of zero crossing of the mains voltage.

In Figure 3 (a) shows waveforms of mains voltage V(IN), input current I(IN), output current I(OUT) of IGBT power converter (drive current of vibratory actuator), DC bus voltage and absolute value of mains voltage ABS{V(in)}. It is observed that the largest voltage drop in the DC link circuit (capacitor CDC) has at intervals, when the electromagnetic vibratory actuator is excited. The maximum value of the actuator triangular current is set to 2A, and thus obtained its duration of 6.4ms (3.7ms increase and 2.7ms decrease). The current of vibratory actuator has an inductive character and energy of its inductance L is back returns to DC link in a decrease time interval of 2.7 ms (in this interval, in fact, conduct the diodes D1 and D2, while transistors Q1 and Q2 are off). This reactive current leads to a slight increase of DC link voltage. In the time interval when conducting transistors Q1 and Q2 (increase of actuator current) is achieved a voltage drop in the DC link circuit, so its charge in a short time provides power network.

This causes the dominant DC input current of the positive half-period of the mains voltage, as shown in Fig.3 (a). The peak value of this current is about 5.5A. This current impulse is very short and its duration is about 0.8ms. In addition to this current pulse, also appears a small and very short (0.4ms) current impulse in the negative half-period of mains voltage, with the amplitude about 0.25A. It is a consequence of the relatively small refilling of capacitors in the DC link, from the mains power. Note, that significant recharge the capacitors performed by the recovered energy through diode D1 and D2 from the inductance of vibratory actuator. In general, the overall regulated VCD is a source of harmonics, but also the DC component of current.

The DC component of the current that the entire drive injected into the mains network is about 75.4mA, as can be seen from the FFT spectral distribution which is shown in Fig.3 (b). In the case where SET impulse lags behind td = 2ms from the moment passing the supply voltage through the zero, is provided a qualitatively new waveform of the input current of VCD. This case is shown in Fig.4. In this case, in fact, the maximum actuator current and maximum mains voltage coincide. In Fig 4(a) are show the characteristic values as in the previous case. Power network takes positive short-impulse current whose amplitude 5.6A, and its duration of about 0.5ms. In fact, in addition to the network of the higher harmonic component takes also a DC current of 80mA, as shown in the spectral distribution of the FFT of Figure 4 (b).

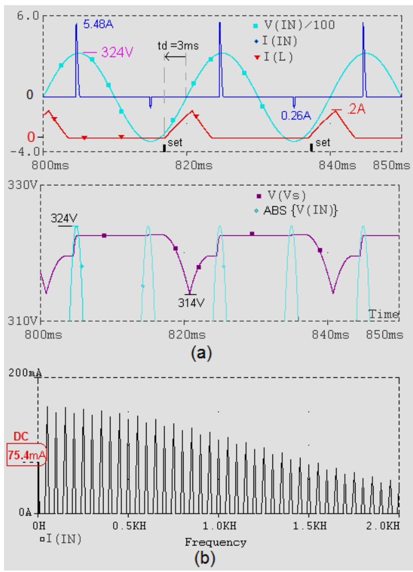

Figure 3. Simulation results for regulated VCD; time leg -2ms (a) characteristics waveforms (b) FFT spectrum

Fig. 5 shows the simulation results for the case of a time delay td = 7ms. Essentially this case is not much different from the first case. The only difference is that in the positive half-period mains voltage is generated current impulse amplitude of 260mA and the negative half-period short-time impulse much larger amplitude i.e. 5.5A. In addition to the higher harmonics, regulated VCD is a source of DC component that is injected into the power network. Its average value is about 73.4mA, as shown in the FFT spectrum.

Fig.6 shows simulation results for the case of a time delay td = 12ms. These results are very similar to those obtained in Fig.4.The only difference is that the input current impulse (current from the mains power) is negative, since it generated in the negative half-period supply voltage. The DC component of the current which is injected into the network in this case is about 79mA.

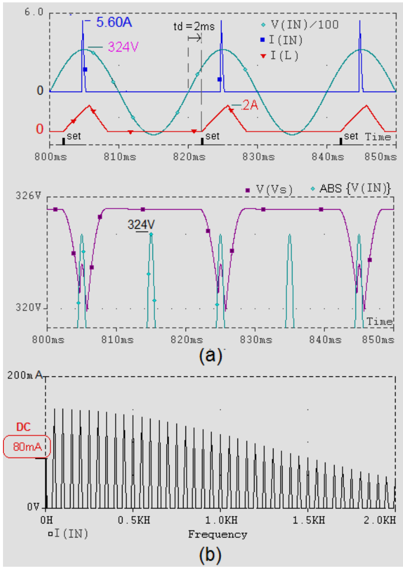

Figure 4. Simulation results for regulated VCD; time leg +2ms, (a) characteristics waveforms (b) FFT spectrum

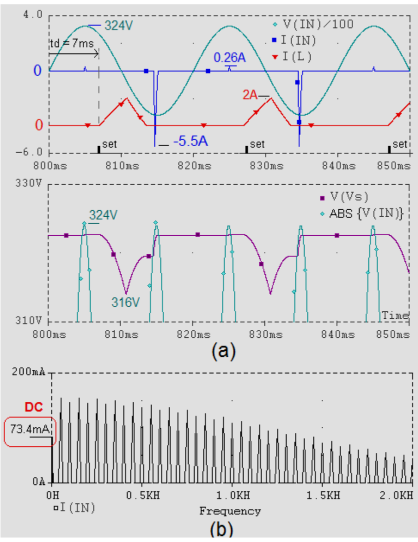

Figure 5. Simulation results for regulated VCD; time leg +7ms; (a) characteristics waveforms (b) FFT spectrum

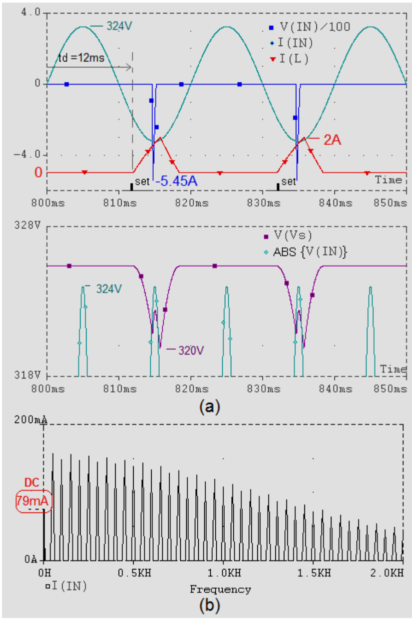

Figure 6. Simulation results for regulated VCD; time leg +12ms (a) characteristics waveforms (b) FFT spectrum

IV. EXPERIMENTAL RESULTS

This chapter presents experimental results for concrete realized regulated resonant VCD, which is described in detail [6-7],[11-13]. Were measured the four characteristic values of interest: mains voltage, the input current of regulated VCD, DC-link voltage (DC bus voltage) and output current of IGBT converter (excitation current of vibratory actuator). The synchronization circuit was adjusting instant of vibratory actuator switching, relative to the zero crossing of mains voltage. In the experiments was obtained the oscilloscopic records of above-mentioned characteristic values, for several cases synchronization.

In Fig. 7 are shown oscilloscopic records of characteristic values for the case when the switching moment of the vibration actuator lead related to zero voltage crossing of the mains voltage, for the time td = 2ms. In the positive half-period of mains voltage is dominant current impulse with maximum value of 6A, while in the negative half-period occurs current pulse whose value is much smaller. In this case, the measured average value of input current (DC injection) is amounted to 85mA.

In Fig. 8 are shown oscilloscopic records of characteristic values for the case when the switching moment of the vibration actuator is delayed related to zero voltage crossing of the mains voltage, for the time td = 2ms. In the positive half-period of mains voltage is dominant unidirectional current impulse with maximum value of 6A. Average value of these pulses (DC component) is equal about 85mA. A similar situation is when there is a time delay equal to td = 12ms (Fig.9), when the input current is unidirectional but negative (in the negative half-period of mains voltage). Its average value as in the previous case was about 85mA.

On the basis of simulation and experimental was demonstrated that, despite the many advantages of transistor regulated VCD using the effect of mechanical resonance, as well as previously mentioned thyristor drives, have a very negative effect on the low-voltage power network, if it is taken as a criterion injections DC current component. For these reasons, the input diode rectifier must be replaced with a specific rectifier, which must have contains an active power factor correction (PFC). Very often, PFC circuits used to provide sinusoidal input current. As standard can be used "boost" converter is placed to DC link of IGBT converter for driving of electromagnet of vibratory actuator [7, 16].

In addition to this standard solution is practically implemented transistor PFC rectifier with two transistors and two diodes, which is described in detail in references [6-8], [17-18]. This solution proved to be very favorable in regulated resonant VCD.

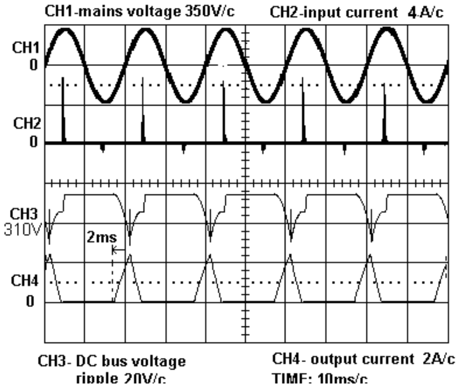

Figure 7. Oscilloscopic waveforms for practically realised IGBT regulated VCD; time leg -2ms

At the end, in this chapter are presented two experimental results related to the suppression of higher harmonics and DC components of the input current regulated VCD. In Fig.10 presents typical waveforms rectifier with PFC, which is placed between the regulated VCD and power networks, for two cases the synchronization (two times legs) of vibratory actuator current pulses and mains voltage. On Fig.10 (a) are shown oscilloscopic records for time leg td=+5ms, while in Fig.10 (b) are shown same waveforms for time leg td=+12ms.

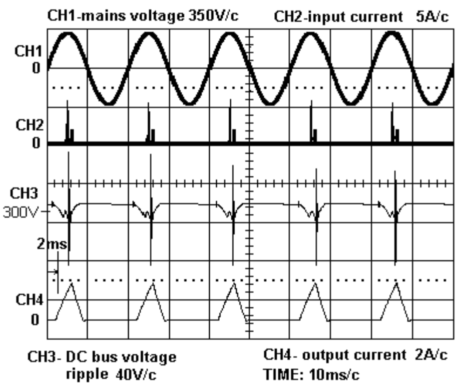

Figure 8. Oscilloscopic waveforms for practically realised IGBT regulated VCD; time leg +2ms

From presented waveforms of the input current, low voltage power network and DC-link voltage of IGBT converter for driving vibratory actuator, it can be clearly seen that the higher harmonics as well as unidirectional current component was completely suppressed

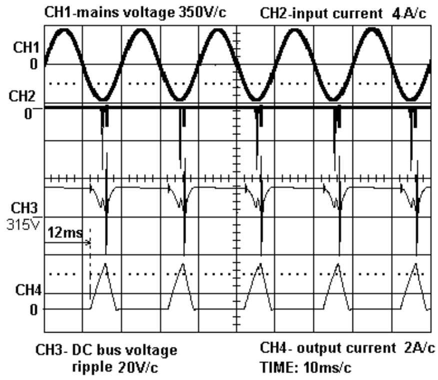

Figure 9. Oscilloscopic waveforms for practically realised IGBT regulated VCD; time leg +12ms

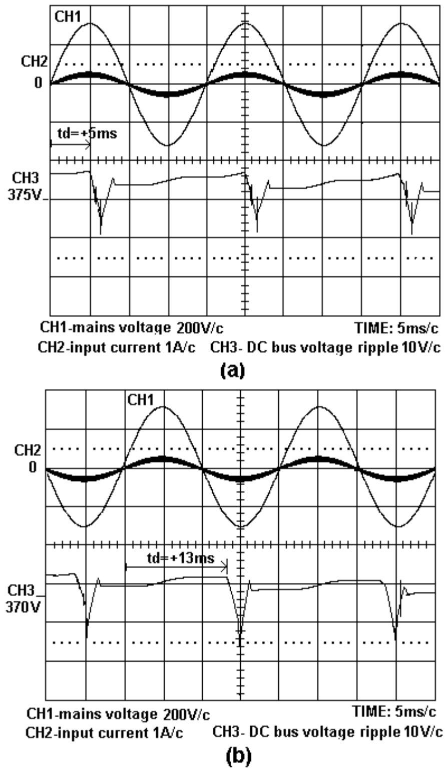

Figure 10. Power factor correction in regulated VCD for different time leg of vibratory actuator current; (a) td=+5ms, (b) td=+12ms.

V. CONCLUSION

In this paper is described the negative impact of regulated VCD to the low voltage power network, despite the many benefits that they offer. Most attention is devoted to IGBT regulated VCD and studied their impact from the aspect of injections DC components in the power network. The examination of this influence is confirmed by simulation and experimental results, which showed very good agreement. At the end it was suggested one possible solution PFC rectifier that is placed between the regulated VCD and mains. To this solution are shown in experimental results. Experimental results was confirmed that the PFC rectifier solution completely suppress higher harmonics and prevent DC injection in power network.

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