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OSCILLATING SYNCHRONOUS PULSATING CURRENT MOTOR-COMPRESSOR SUPPLIED FROM DC SOURCE

ABSTRACT *This paper deals with the oscillating synchronous pulsating current motor driving a piston compressor that is supplied from DC source by converter, which forms square-wave voltage impulses. The studies of supply of this motor from DC source are related to problems of its control as well as to enlargement of domains of its application (e.g., in the road vehicles).*

The main advantage of considered device is a possibility to connect directly moving part of the motor with the compressor's piston. The oscillating synchronous motors are used in this drive. Practically, two types of oscillating synchronous motors are applied in the compressor drive: the excited and so-called pulsating current motors (with the unidirectional impulses of windings current formed by semiconductor element or by supplying converter [1]). The simplest pulsating current motor in the single-sided compressor drive is shown in Fig.3a). As a rule, a mechanical spring is necessary in such device [3]. However, the symmetric pulsating current motor in the double-sided compressor drive (Fig.3b) in principle could be springless.

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A thyristor-control of studying motor is the simplest. The frequency control also can be realised by inverter, which forms a sinusoidal voltage using filters of higher harmonics. Any type of filters makes more expensive the converter itself. The simpler converter is that, which forms square-wave voltage impulses. In this case, converter would be composed of electronic switches. Two followed in turn voltage pulses of different signs must be formed, as only in such case the recuperation of magnetic field energy is possible. The requirements for square-wave supplying voltage are reflected it Fig.4a). The duration of the positive voltage pulse T_1 *predetermines motor performance, and the duration of this pulse could be varied dependably on purpose of control. The duration of negative pulse* T_2 *must continue till the current* i *become equal to zero. If the inverse current is limited by additional element of the circuit, the duration of negative pulse* T_2*' must continue up to the end of cycle. The square-wave voltage may be formed from direct voltage with an* H*-shape scheme of electronic switches* S *(Fig.4b).*

The analysis of such motor-compressor drive has been carried out by numerical methods (in Mathcad software). Some variables and characteristics of considered motor as functions of oscillation amplitude H on complex mechanical impedance $\underline{Z}=R + jX$ *[1] are presented in Fig.5, 6, 7. The results of analysis show that it is expedient to supply the oscillating synchronous pulsating current motor-compressor from DC source by forming the square-wave voltage. In this case the control of the device can be carried out more easily.*

1. INTRODUCTION

The main advantage of piston (or diaphragm) compressor driven by oscillating electrical motor is a possibility to connect directly moving part of the motor with the compressor's piston. Some principles of application of such motor-compressor we have presented in the previous our paper [1]. It is worth to remind that in this direct drive the mechanical transformer is avoided. Thus, an efficiency of the drive is increased, while dimensions and the cost are decreased. Therefore the compressor drive with oscillating motor is popular and topical for small compressors (approximate up to 1 kW), namely for compressors of household refrigerating devices [2].

Most likely, Paul Boucheraut at France had tested the first compressor driven by oscillating electrical motor in the beginning of 20th century [3]. Later these compressors were actively created and studied during different periods and in various countries. Actually, the Korean firm *LG Electronics* started successfully manufacturing household refrigerator [2]. The famous producers of the compressors for refrigerators like *Electrolux, Embraco* also started to create such motor-compressors of last years. Our studies of oscillating electrical motors and compressors driven by these motors were started in 1960 (by one of the authors of this paper S. Kudarauskas). So, our studies look like as the longest ones (more than 40 years).

In spite of existing attention for considered devices of many years, there are many unsolved problems yet, partly because of their multidisciplinary nature. For instance, even the terms of such devices are still not settled. In some cases the piston compressor driven by oscillating electrical motor are called as the *linear compressor* (e.g., [2], [4]), though such devices with other trajectory of movement also exist [3]. The main feature of the considered device is fact that the oscillating electrical motor drives the volumetric reciprocating compressor. This circumstance could be best defined by the term *oscillating motor-compressor*.

Of course, the oscillating motors of very different structures are applied and proposed for the compressor drive. Through this paper deals with so-called synchronous *pulsating current* motor, but some other possible structures are presented too. The studies of possible supply of this motor from DC source (in fact, from direct voltage source) are related to problems of its control as well as to enlargement of domains of its application (e.g., in the road vehicles). Thus, the DC source can be understood directly or as the intermediate section of converter supplied from AC source.

2. OSCILLATING MOTORS IN THE COMPRESSOR DRIVE

The oscillating *synchronous* motors are used in the compressor drive. The strict relation between the frequencies of mover oscillations and supply voltage (or supplies voltages) determines the synchronism of oscillating machine. Practically, two types of oscillating synchronous motors are applied in the compressor drive: the *excited* motors (as a rule, with permanent magnets) and so-called *pulsating current* motors (with the unidirectional impulses of windings current formed by semiconductor element or by supplying converter [1]).

An oscillating synchronous excited machine (as the all classical synchronous machines) has two sources of magnetomotive force: alternating mmf and permanent mmf. In Figure 1 the oscillating linear synchronous excited motor in the drive of double-sided piston compressor is shown. In this figure presented motor has the mmf sources (AC and DC windings) in different parts of the stator. In Figure 2 variants of analogous motors with permanents magnets are shown. As we see, the exciting magnets can be mounted in machine's stator as well as in the mover, but this circumstance in principle does not change performances of motor. Of course, there is great variety of possible variants of structures of oscillating synchronous excited machines.

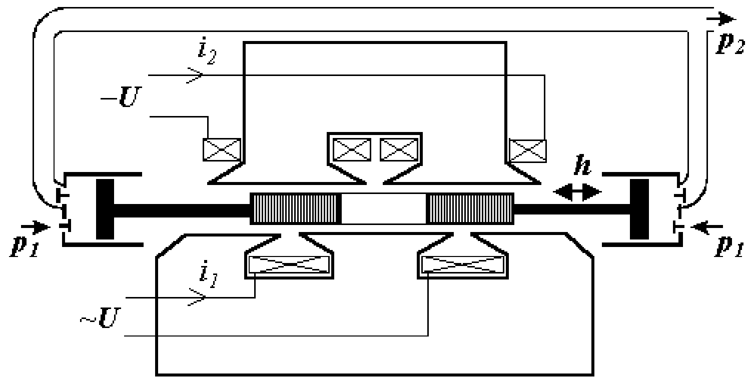

Fig.1. Oscillating motor-compressor with synchronous excited motor

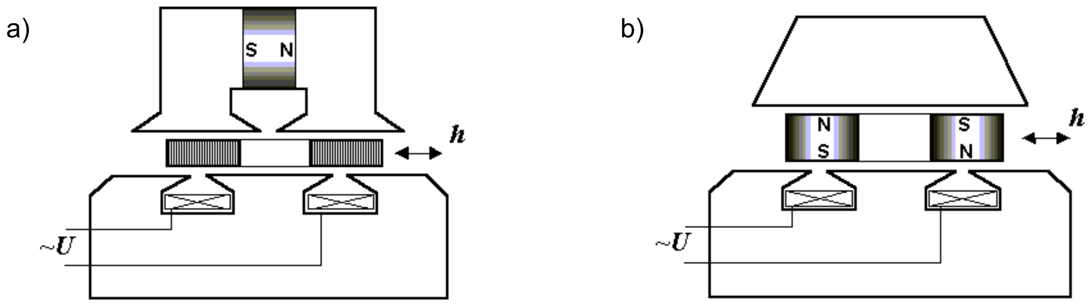

Fig.2. Oscillating synchronous excited motors with permanent magnets in stator (a) and in mover (b)

In Figure 3a) the simplest (asymmetric) pulsating current motor in the single-sided compressor drive is shown. As a rule, a mechanical spring is necessary in such device, as the deformation of which can balance the continuous components of motor and compressor forces. In Figure 3b) symmetric (doubled) pulsating current motor in the double-sided compressor drive is shown. In principle, this device could be springless. A supplying converter (*square-wave voltage block*) used instead of a conventional semiconductor element served for the pulsating current motor is depicted in Fig.3b). However, this replacement does not change the principle of operation of this motor.

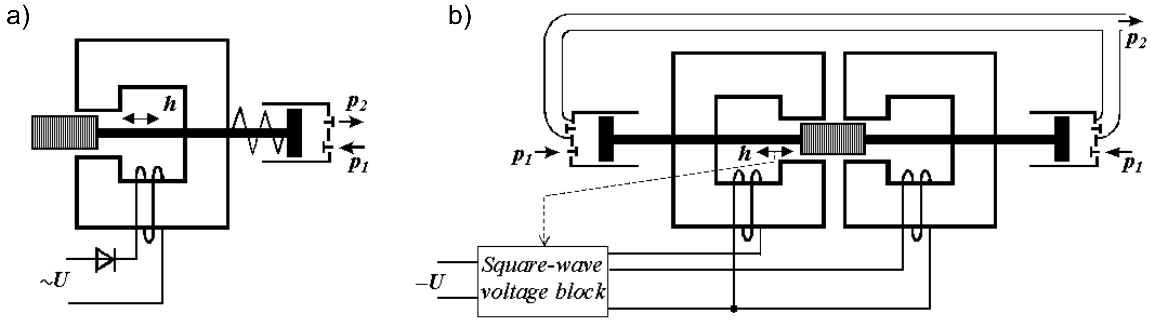

Fig.3. Oscillating synchronous pulsating current motors-compressors

As it was mentioned in the introduction, in many cases a supplying of oscillating motor from DC source is related to the problems of its control. Therefore, from this point of view the requirements for such kind of supplying are described below.

3. REQUIREMENTS FOR THE SUPPLYING CONVERTER

The oscillating synchronous excited motors (see Fig.1-2) could be controlled by variation of the exciting current (if the exciting winding does exist) or by variation of supplying alternating voltage, including a frequency control. The simplest control of the pulsating current motor is the thyristor-control (when the unidirectional pulses of current are formed by thyristor). The frequency control of these motors also can be applied (e.g., for larger possibilities to vary of the compressor capacity). We have such situation when the DC source directly supplies the motor as well as when the DC section is used in the cycloconverter. The same situation exists in the self-controlled DC motor, as it is shown in Fig.3b) by dashed line of interconnection between the co-ordinate of mover h and converter block.

In case of frequency control, the corresponding inverter or cycloconverter could form a sinusoidal voltage. In this case, the sinusoidal voltage could be formed using modulated voltage impulses and filtering higher harmonics of output voltage. So, any type of filters should be composed with elements of energy storage, that could complicate and make more expensive the converter itself.

The simpler converter is that, which forms square-wave voltage impulses. In this case, converter would be composed of electronic switches without the output voltage filters. Two followed in turn pulses of different signs must be formed, as only in such case the recuperation of magnetic field energy is possible. It is worth to remind that such situation exists when the alternating voltage supplies a pulsating current motor [1].

The requirements for square-wave supplying voltage of the asymmetric pulsating current motor (see Fig.3a) or of the one section of the symmetric motor (see Fig.3b) are depicted it Fig.4a) by dotted line (here T is duration of the cycle). The duration of the positive voltage pulse T_1 predetermines motor performance, and the duration of this pulse could be varied dependably on purpose to control. The duration of negative pulse T_2 must continue till the current *i* become equal to zero (if this duration should be longer, a negative current could arise). If the inverse current is limited by additional element of the circuit, the duration of negative pulse T_2' must continue till the end of cycle. In this case the control of duration of the negative voltage pulse can be avoided, and the converter could be simpler.

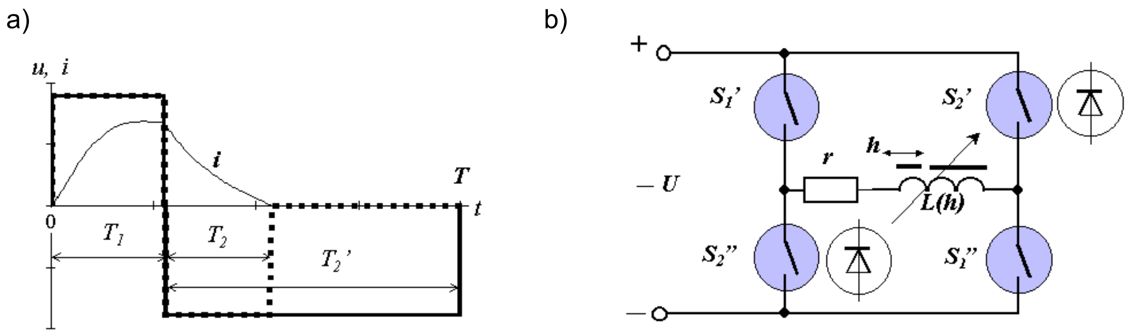

Fig.4. The square-wave voltage (a) and the principle of circuit for its formation (b)

The square-wave voltage may be formed from direct voltage with an H-shape scheme of electronic switches S (Fig.4b). Here the pulsating current motor is presented by inductance $L(h)$ which depends on the mover co-ordinate h. In fact, the switchers S_2' and S_2" can be replaced by diodes (they are depicted beside the switches in Fig.4b); in this way the H-shape scheme can be simplified.

4. CHARACTERISTICS OF MOTOR

The supplying of oscillating motor-compressor by square-wave voltage formed from DC source is already known [4], but it is not studied sufficiently.

So, the analysis of such motor-compressor drive has been carried out by numerical methods (in Mathcad software).

In Figure 5a) the variables of the starting of considered motor are presented. The curves of Fig.5b) show as the current of motor depends on duration of the positive pulse of supplying voltage. As we see, the waveform of current during positive and negative voltage pulses can be very different (e.g, when T_1=0.5 T) or similar (e.g, when T_1=0.2 T). In last case, almost only pulsation of reactive power is observed (but not electromechanical conversion of energy). So, it is possible to control motor operation by variation of duration of the first voltage pulse.

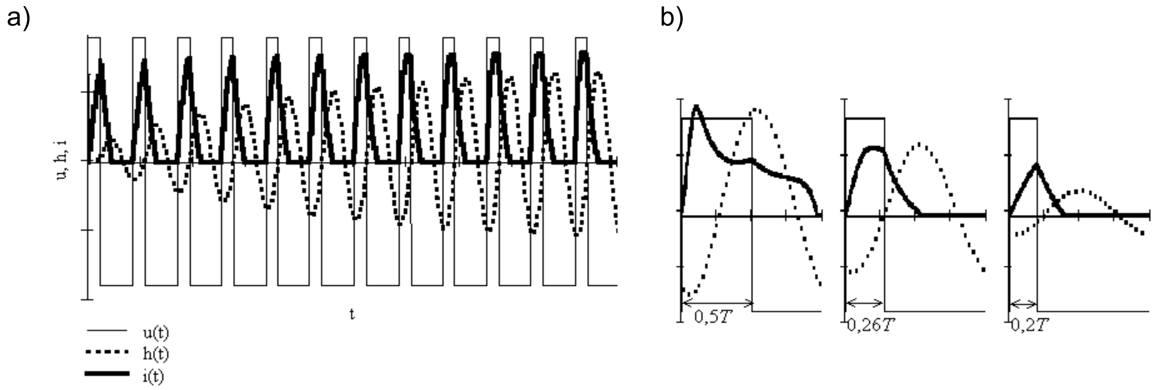

Fig.5. Starting of the pulsating current motor supplied by square-wave voltage (a) and controllable variables (b)

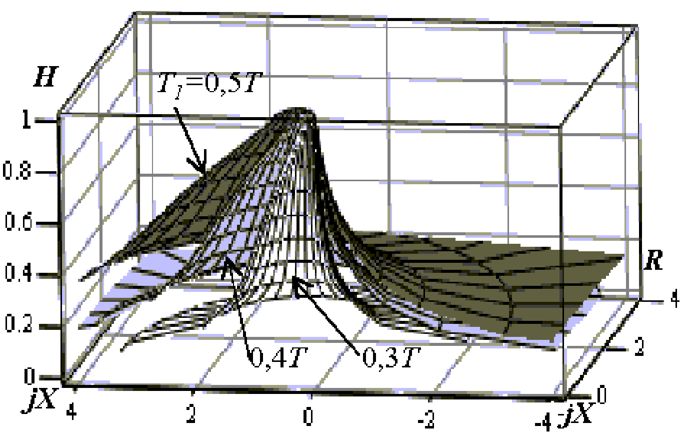

Fig.6. Motor characteristics *H(Z)* when T_1 changes

The characteristics of considered motor as functions of oscillation amplitude on complex mechanical impedance $\underline{Z}=R + jX$ [1] are presented in Fig.6. As we see, these characteristics graphically are interpreted as 3D surfaces. The different duration of supplying impulse forms an appropriate surface, which defines the motor performance.

Modelling and simulation of the oscillating synchronous pulsating current motor-compressor enables to study whole processes of this complex non-linear device. For instance, in Fig.7 the variables of starting are shown (including pressure in the compressor cylinder).

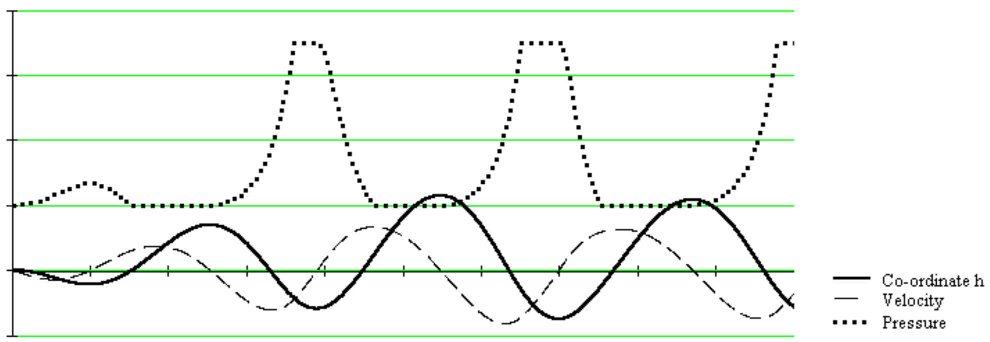

Fig.7. Variables of the motor-compressor starting

5. CONCLUSION

The results of analysis show that it is expedient to supply the oscillating synchronous pulsating current motor-compressor from DC source by forming the square-wave voltage. In this case the control of the device can be carried out more easily.

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ZESPÓŁ SILNIK OSCYLUJĄCY SYNCHRONICZNY-
-KOMPRESOR ZASILANY PRĄDEM PULSUJĄCYM
ZE ŹRÓDŁA PRĄDU STAŁEGO

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STRESZCZENIE *Artykuł dotyczy zespołu oscylacyjny silnik synchroniczny – kompresor tłokowy, zasilanego prądem pulsującym otrzymywanym ze źródła prądu stałego poprzez przetwornik wytwarzający prostokątne impulsy napięcia. Badania dotyczące zasilania tego silnika ze źródła prądu stałego są związane z problemami jego sterowania oraz z rozszerzeniem obszaru jego zastosowania (np. w pojazdach drogowych).*

Główną zaletą rozpatrywanego urządzenia jest możliwość bezpośredniego połączenia ruchomej części silnika z tłokiem sprężarki. W napędzie tym stosuje się oscylacyjne silniki synchroniczne. W praktyce do napędu sprężarki stosuje się dwa rodzaje oscylacyjnych silników synchronicznych: silniki ze wzbudzeniem i tzw. silniki na prąd pulsujący (z jednokierunkowymi impulsami prądu uzwojenia formowanymi przez element półprzewodnikowy lub przez przetwornik zasilający [1]). Rysunek 3a) przedstawia najprostszy silnik na prąd pulsujący w jednostronnym napędzie sprężarki. W urządzeniu takim z zasady potrzebna jest mechaniczna sprężyna [3]. Jednakże dwustronny napęd sprężarki (rys.3b) silnikiem na symetryczny prąd pulsujący z zasady może być bez sprężyny.

Najprostsze jest tyrystorowe sterowanie rozważanych silników. Sterowanie częstotliwościowe może być również realizowane przez falownik, który daje napięcie sinusoidalne przy użyciu filtrów wyższych harmonicznych.

Wszelkie filtry podrażają przetwornik. Przetwornik wytwarzający impulsy fali prostokątnej jest prostszy. W tym przypadku przetwornik składałby się z przełączników elektronicznych. Muszą być wytworzone następujące po sobie kolejno impulsy napięcia różnego znaku, gdyż tylko w tym przypadku jest możliwe odzyskiwanie energii pola magnetycznego. Wymagania dla napięcia o przebiegu prostokątnym

napięcia zasilającego przedstawiono na rys.4a). Czas trwania dodatniego impulsu, T_1, decyduje o pracy silnika i może być zmieniany zależnie od potrzeb sterowania. Czas trwania impulsu ujemnego, T_2, musi trwać, aż prąd i stanie się równy zeru. Jeśli prąd wsteczny jest ograniczony przez dodatkowy element obwodu, to ujemny impuls, T_2', musi trwać do końca cyklu. Napięcie o przebiegu prostokątnym może być wytwarzane z napięcia prądu stałego przez układ typu H przełączników elektronicznych S (rys.4b).

Analizy takiego napędu motor-kompresor dokonano metodą numeryczną (przy użyciu programu Mathcad). Niektóre zmienne i charakterystyki rozpatrywanego silnika pokazano na rys.5, 6, 7 w funkcji zależności amplitudy oscylacji H od zespolonej impedancji mechanicznej $\underline{Z} = R + jX$ [1]. Wyniki analizy wykazują, że korzystne jest zasilanie zespołu oscylacyjny silnik synchroniczny-kompresor, prądem pulsującym ze źródła prądu stałego, przez formowanie napięcia o przebiegu prostokątnym. Pozwala to na łatwiejsze sterowanie urządzenia.