Determination of conditions for optimal control of a permanent magnet synchronous motor of a single-stage reciprocating compressor for a proposed law of motion for ensuring the maximum efficiency

A A Tatevosyan
Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
E-mail: karol@mail.ru

Abstract. Attention is paid to issues of reliability and economy while ensuring high performance of energy conversion processes occurring in various subsystems when a linear magneto-electric drive (LMED) is designed, which includes a permanent magnets synchronous motor with permanent magnets (PMSM) and a compressor stage. Reducing the number of elements included in the LMED, for example, transmission and conversion mechanisms is one of the directions that increase the reliability of the LMED. However, in this case, non-linear suction-discharge processes occurring in the compressor stage have a significant effect on the operation of the electromechanical converter. In this regard, the task of improving the energy efficiency of LMED can be solved in various ways. The article describes the LMED control conditions of a low-speed single-stage piston compressor, obtained from the solution of the problem of optimizing the design of the magnetic system PMSM, at which maximum efficiency is achieved. The relationship of the generalized parameters of the drive with the design features of the PMSM is established.

1. Introduction
The working process of energy conversion in the magneto-electric drive of reciprocating motion of the piston compressor is influenced by numerous factors that can be expressed in optimizing the design of the LMED through the generalized parameters of the power source, magnetoelectric engine and compressor [1-5, 9-12].

These include:
for power supply
– maximum value of voltage at motor winding, phase angle of shift between armature motion law and compressible gas resistance force, frequency of supply voltage;
for magneto-electric motor
– active resistance and inductance of motor winding, induction in air gap, armature stroke;
for compressor
– average value of power transmitted to mechanical system, piston stroke.

Preliminary calculations indicate that the law of movement of the piston can significantly affect the efficiency of the working process of piston slow-moving long-stroke stages [6-8]. However, the issues of synthesizing energy-saving laws of movement and reducing the unevenness of the change in instantaneous power in relation to compressor units with linear drive were not considered in available sources of information. The ambiguous functional relationship between the efficiency of the compressor stage working process, integral characteristics and the law of movement of the compressor
rod makes it relevant to study their relationship and the possibility of improving the energy and dynamic characteristics of a single-stage compressor unit with a linear magneto-electric motor. Figure 1 shows the magnetic system of the linear magneto-electric motor as part of the drive of the low-speed single-stage piston compressor LMED. The functional element of the unit is a slow-moving long-run compressor stage.

Figure 1. Magnetic system of PMSD: 1 – synchronous motor; 2 – compressor piston; 3 – control system, 4 – armature; 5 – winding; 6 – anchor; 7 – permanent magnets.

The task of optimizing the structures of magnetic systems in PMSM is associated with taking into account the peculiarities of the working process of electrical complexes in which they are used as electromechanical converters. The maximum possible efficiency is possible if the condition of the identity of the laws of current change in the motor winding and the speed of the rotor movement in time, that is, \( i(t) = \dot{\vartheta}(t) \) is satisfied.

2. Task setting and its mathematical formulation

Setup in the LMED mathematical model the law of armature motion in time as an initial approximation, guided by the iterative procedure of the Schwartz method, leads to simplification of analysis of electromagnetic and mechanical processes and solution of equations of dynamics of the electric part of the drive regardless of processes in the mechanical part. Set the law of moving parts of LMED in the form of

\[
x(t) = x_m \left[ 1 - \cos(\omega t) \right],
\]

where \( x_m \) – half amplitude moving part, \( \omega = \frac{2\pi}{T} \) – angular frequency, \( T \) – oscillation period.

For purposes of electric drive of piston compressor, sinusoidal law of piston motion is most preferable, since theoretically it excludes piston impacts against cylinder walls [13].

Taking into account the expression (1), the dynamic force in the motion equation of the moving parts

\[
m \frac{d\vartheta}{dt} = F_{dyn} = mx_m \omega^2 \cos(\omega t),
\]

Expression of the evolving electromagnetic force PMSM

\[
F_e = cI_m \sin(\omega t),
\]

Expression of compressible gas resistance force in long-run compressor

\[
F_g = 99N_am_\beta \frac{\pi d^2}{4} \sin(\omega t + \omega t_k),
\]
where \( x_m \) – half of armature moving, \( m \); \( m \) – weight of mobile part PMSM, kg; \( c = B_m i_m k \) – machine constant, \( T \cdot m \); \( N_{atm} = 10^5 \) Pa, – atmospheric pressure; \( \omega t_k \) – control angle, rad.

After substitution (2) – (4) in the dynamics equation

\[
\frac{d\theta}{dt} = \frac{F_c - F_g}{c} - \left[ mx_m \omega^2 \cos(\omega t) \right] - \left[ F'_g \sin(\omega t + \omega t_k) \right],
\]

where \( F'_g = 99N_{atm}\beta \frac{\pi d^2}{4} \).

To determine the amplitude of the current \( I_m \) and angle \( \omega t_k \) use the following expressions:

\[
I_m = \sqrt{F'^2 - (mx_m \omega^2)^2} / c, \quad \omega t_k = \pi + \arctg \left( \frac{mx_m \omega^2}{cI_m} \right)
\]

or

\[
\omega t_k = \pi + \arctg \left( \frac{1}{\sqrt{k_0} - 1} \right),
\]

where \( k_0 = 99 \frac{N_{atm}\beta \pi d^2}{4mx_m \omega^2} \).

3. Modeling Results

Results of LMED dynamic characteristics calculation are given in Fig. 2.

The phase shift between \( F_g = F'_g(t) \) and \( F_c = F_c(t) \) is due to the presence of dynamic force \( F_{dyn} = F_{dyn}(t) \).

The piston compressor is used to maintain pressure in the main by means of a special intermediate link - receiver [6-8, 13, 14]. The receiver is a vessel whose gas pressure is controlled by an inlet and outlet valve system. When the specified pressure is reached, the piston compressor is disconnected, when the pressure in the receiver decreases, the compressor is turned on, injecting gas into the receiver tank. Thus, the operation modes of the PMSM are possible, in which the piston does not make a complete movement, squeezing the gas into the receiver, while the pressure in the latter reaches the necessary value.
In order to achieve an optimal LMed mode of operation, in which the specific losses will be minimal, it is necessary that the time dependencies of the current and the speed of the moving parts coincide in phase. To do this, calculate the angle $\theta$ of the initial stress phase:

$$\theta = \arctg \frac{I_m \omega L}{I_m R + C x_m \omega}$$

(8)

Using the developed simulation model, we determine the dependence of the supplied voltage on the PMSM winding on the LMed load factor when using the receiver (Fig. 3).

![Figure 3. Voltage from power factor](image)

Failure to take into account the adjustment of the initial voltage phase leads to an increase in the transition time, at which the optimal law of movement of the movable part is achieved: $i(t) = \delta(t)$.

The time dependencies of the current in the winding with the speed of the armature movement without taking into account the angle $\theta$, as well as when the control system compensates the reaction force of the compressor stage (Fig. 4)

![Figure 4. Time dependence of current $i(t)$ (1) and inductor speed $\delta(t) \times 20$ (2) without setting the initial phase $\theta$ of voltage (a) by the control system and with adjustment by angle $\theta$ (b).](image)

With a sinusoidal load change law (4), the minimum possible relative losses of the PMSM, which means the maximum engine efficiency

$$\eta_{d, max} = (1 + \frac{P_{r min}^*}{P_{r, min}})^{-1}$$

(9)

where $P_{r, min}^* = \frac{R I_m}{C x_m \omega}$. 

4
Thus, the control system should provide a sinusoidal motion of the armature, at which minimum relative losses in the PMSM are possible.  
As an example, consider PMSM with the parameters shown in Table 1.

### Table 1. PMSM parameters

| Parameter Name                      | Parameter Value |
|-------------------------------------|-----------------|
| Resistance, Ohm                     | 4               |
| Inductance, H                       | 0.12            |
| Air Gap Average Induction, T        | 0.4             |
| IW winding                          | 2200            |
| Anchor Mass, kg                     | 45              |
| Anchor Moving, m                    | 0.2             |
| Frequency, Hz                       | 1               |
| Diameter piston, m                  | 0.02            |
| Voltage: $U = U_{in} \sin(\omega t + \theta)$, where $U_{in} = 180 \, V$, $\theta = 0.0338 \, \text{rad}$ |
| Gas Force: $F_g = F_{gin} \sin(\omega t + \omega t_k)$, where, $F_{gin} = 3110 \, N$, $\omega t_k = 0.0572 \, \text{rad}$ |

The dependence of the phase angle between the traction electromagnetic force and the armature stroke, as well as the dependence PMSM efficiency of action on the power factor is shown in Fig. 5.

![Figure 5](image)

**Figure 5.** Phase shift angle dependence between compressible gas resistance force and current in winding (a) and efficiency of action (b) on LMED power factor.

Solution-set optimization of analytical relationship of generalized PMSM parameters providing maximum efficiency of electromechanical converter allows to determine relative losses in PMSM subsystems $P'_{\text{min}} = 0.2182$ and maximum possible efficiency for the proposed design $\eta_{d, \text{max}} = 82.1\%$

### 4. Conclusions

As a result of the study, an expression is obtained for determining the optimal phase shift angle between the resistance force of the compressed gas in the long-pass compressor stage without lubrication of the working chamber and the speed of movement of the movable parts, as well as the initial phase of the supply voltage, which make it possible to achieve the maximum possible efficiency PMSM in the linear reciprocating drive.
5. References

[1] Ismagilov F R, Vavilov V E, Miniyarov A H, Urazbakhtin R R 2018 Super high-speed electric motor with amorphous magnetic circuit for the hydrogen fuel cell air supply system *International Journal of Hydrogen Energy*, Vol 43, Issue 2414 June P 11180–11189

[2] Nikitenko G V, Konoplev E V, Devederkin I V 2013 High-performance synchronous generator with permanent magnets for wind power plant *Bulletin of Stavropol agriculture* No 4 (12). Pp 80–84

[3] Vavilov V E 2018 The choice of the rotor magnetic system for electromechanical energy converters with coercivity magnets *Journal of mechanical engineering* 1 Pp 26–29

[4] Adalev A S Kuchinskiy V G 2015 Linear electric motor with permanent magnet excitation for cargo magnetic levitation transport platform *Transport systems and technologies* vol 1 (1) P 77–90. DOI: 10.17816/transsyst.20151177-90

[5] Tatevosyan, A, Kovalev, V Mathematical Modeling of the Linear Drive for Research Viscoelastic Properties of Elastomer *12th International Scientific and Technical Conference "Dynamics of Systems, Mechanisms and Machines", Dynamics 2018*, 8601426

[6] Vyngra A V, Avdeyev B A, Abdurakhmanov R F, Yenivatov V V and Ovcharenko I K 2019 “Mathematical Model of Start for a Piston Compressor Electric Drive of a Ship Refrigerator,” in 2019 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus) pp 373–376

[7] Yusha V L, Busarov S, and Nedovenchanyi A V 2018 “Analysis of the operating cycle efficiency of the long-stroke slow stage under the changing ratio of the piston forward and backward stroke time,” in *AIP Conference Proceedings* vol. 2007, 030058

[8] V L Yusha, Busarov S S, and Gromov A Y 2017 “Assessment of the Prospects of Development of Medium-Pressure Single-Stage Piston Compressor Units,” Chem. Pet. Eng., vol 53, no. 7–8 pp 453–458 Nov

[9] Chun T, Ahn J, Lee H, Kim H, and Nho E 2008 “A Novel Strategy of Efficiency Control for a Linear Compressor System Driven by a PWM Inverter,” IEEE Trans. Ind. Electron., vol 55, no. 1, pp 296–301

[10] Akita S, Higuchi T, Yokoi Y, Abe T, Shirotani T, and Makino S 2017 “Design analysis of a line-start permanent magnet linear synchronous motor,” in 2017 11th International Symposium on Linear Drives for Industry Applications (LDIA) pp 1–4

[11] Cui F, Sun Z, Xu W, Zhou W, and Liu Y 2020 “Comparative analysis of bilateral permanent magnet linear synchronous motors with different structures,” CES Trans. Electr. Mach. Syst., vol 4, no 2, pp 142–150

[12] Poltschak F, “A high efficient linear motor for compressor applications,” in 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2014, pp. 1356–1361

[13] Ang S, Rong-ming C, and Hui-xing Z 2011 “Research on the iterative learning control method for linear motor driven compressor,” in 2011 International Conference on Electrical Machines and Systems pp 1–4

[14] Letter H, “The Sulzer Oil-Free Labyrinth Piston Compressor 1972 ” International Compressor Engineering Conference/School of Mechanical Engineering Purdue University pp 220–228