ISSN 1068-3712, Russian Electrical Engineering, 2024, Vol. 95, No. 6, pp. 512–519. © Allerton Press, Inc., 2024.
Russian Text © The Author(s), 2023, published in Energeticheskie Ustanovki i Tekhnologii, 2023, Vol. 9, No. 1, pp. 99–107.

Self-Oscillatory Processes in Pulse-Width Regulation of Phase Voltages of a Direct Current Valve Motor

V. E. Vysotsky*
Sevastopol State University, Sevastopol, 299053 Russia
**e-mail: vitalyvysotsky@mail.ru*

Received February 1, 2022; revised February 3, 2023; accepted April 23, 2024

Abstract—In this article, the physical features of electromagnetic and electromechanical processes in regulated dc valve motors with pulse-width modulation of voltage on armature are considered. The features of the influence of position-dependent switching and control on the functioning of such valve electromechanical systems are analyzed. In rowing electric drives of mobile objects, the use of an adjustable motor of this type has an advantage compared with an asynchronous clock-controlled motor with a short-circuited rotor, which provides the necessary number of consecutive smooth starts.

Keywords: electric propeller drive, smooth starts, reverse, valve motor, electromagnetic excitation, armature winding, pulse width control, self-oscillating processes

DOI: 10.3103/S1068371224700585

INTRODUCTION

In the relatively short period of time that has passed since the appearance of the first industrial batches of valve motors (VMs) on resistors and transistors, various methods for implementing position-sensitive control and switching methods of controlled valve switches (CVCs) have been developed [1, 2]. In this regard, two main trends in the considered field of electromechanics have appeared. One of them consists in the improvement of circuits and designs of valve motors based on modern power semiconductor technology and integrated electronics, and the other consists in an in-depth theoretical study of such machines. Both these trends are closely interrelated and are caused by a number of problems in creating an economical and highly reliable brushless dc electric drive. Among them, the problems of switching and dynamic stability, as well as the impact of positional feedback on the complex of electromagnetic and electromechanical processes in a VM, should be noted (Fig. 1).

Identification of the characteristic features of this class of valve electromechanical systems, regardless of specific circuit options and areas of application, will allow establishing their most general properties. This, in turn, will make it possible to analyze the most complex transient processes, as well as determine the conditions for the static and dynamic stability of the object under study.

The electromagnetic interaction between the inductor and the armature winding of a synchronous electric machine of an VM flown around a nonsinusoidal current introduces significant specificity into the process of energy conversion and its operational characteristics.

Rotational speed ω in an electric drive with a VM can be regulated by changing voltage on the armature winding Ua and weakening the main magnetic flux. In a VM with permanent magnets, the flux is weakened by changing the flux linkage of the equivalent armature winding by adjusting the control angle of the CVC. The regulation of ω for VM by changing U_a has its own pecularities and requires more careful study.

In propulsion electric drives of moving objects, the use of an adjustable motor of this type has the advantage, compared with an asynchronous frequency-controlled motor with a squirrel-cage rotor, that provides the required number of smooth starts and reversals.

This paper considers the features of regulating the rotation speed of a dc VM on fully controlled valves with electromagnetic excitation.

PURPOSE AND OBJECTIVES OF THE WORK

The goal is to identify the features of pulse-width regulation (PWR) of voltage on the armature winding

This is achieved

— first, by presenting the voltage curve in the form of a harmonic series and analyzing the influence of the duty cycle of PWR on the “useful” component and the spectrum of harmonics;

— second, by assessing the qualitative and quantitative composition of currents flowing through both circuits of the machine under PWR for various laws of distribution of magnetic induction along the air gap;

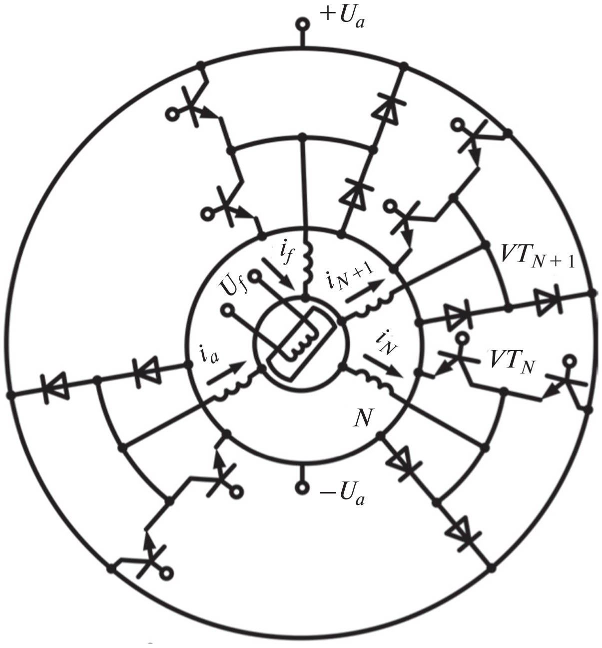

Fig. 1. Electromagnetic circuit of an *m*-phase VM with CVCs on fully controlled valves.

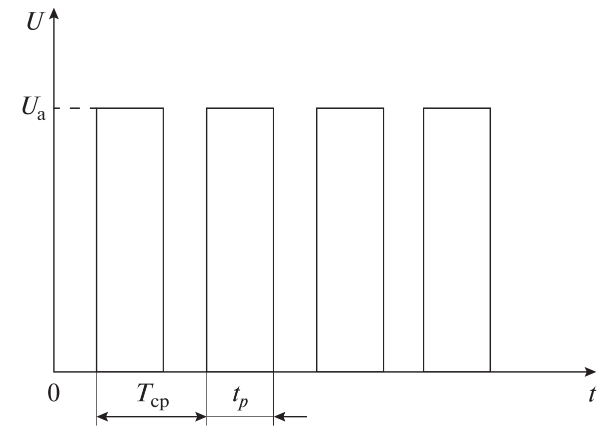

Fig. 2. Voltage on VM armature at PWR.

— third, by studying the influence of combinational harmonics of currents and components of the electromagnetic torque of infralow frequencies on the stability of engine operation.

RESEARCH RESULTS

Under PWR, CVC power valves periodically open and close during the interval of their operation in accordance with the amount of voltage supplied to the motor (Fig. 2).

This voltage curve can be represented as a harmonic series:

$$U(t) = U_a^0 + \sum_{\substack{r=-\infty \\ r \neq 0}}^{\infty} U_a^r e^{j(r\Omega t + \phi_r)}, \tag{1}$$

$$U_a^0 = U_a \frac{\tau\xi}{2\pi}, \quad U_a^r = (-1)^r \frac{U_a}{r\pi} \sin\frac{r\tau\xi}{2},$$

where Ω is the frequency of the fundamental harmonic of the alternating voltage component, $\tau = \frac{t_{\text{operating}}}{T_{\text{cp}}}$ is the duty cycle of control pulses, and $\xi = \Omega/\omega$ is the switching frequency factor to the main rotation speed.

Constant component U_a^0 is decisive for the motor speed and torque. By changing the ratio $\tau = t_{\text{operating}}/T_{\text{cp}}$, one can adjust the value U_a^0, thereby setting the operating mode of the engine. Analysis of expression (1) shows that, with decreasing duty cycle τ, constant voltage component U_a^0 changes proportionally to τ.

Variables U_a^0 at fully open valves ($\tau = 1$) are equal to zero, and, with decreasing τ, the amplitude values of U_a^0 change according to the dependences presented in Fig. 3. At $\tau = 0.5$, the first voltage harmonic reaches its maximum value, whereas constant component U_a^0 has a significantly smaller value than at $\tau = 1$.

Electromagnetic processes in a valve motor controlled using PWR will thus differ from the processes in a valve motor, the supply voltage of which does not contain variable components.

To assess the qualitative composition of the currents flowing through both circuits of the machine under PWR, we note the following.

The assumption of linearity of the valve motor allows one to apply the principle of superposition, due to which the current flowing through the circuits of the machine will be equal to the sum of the currents arising from each component of the applied voltage.

For the case of a sinusoidal law of induction distribution in the air gap, when a constant voltage armature is connected to the winding, a current of the following form flows through it:

$$i_a(t) = \sum_{S=-\infty}^{\infty} I_a^S e^{jS\theta t}, \quad \theta = 2m\omega.$$

For the *r*th harmonic of the applied voltage, a particular solution of the system of VM equations [3] will be

$$i_a(t) = \sum_{S=-\infty}^{\infty} I_a^{r,S} e^{j(r\Omega + S\theta)t},$$

and, taking into account all voltage components (1), the armature current can be represented by the following expression:

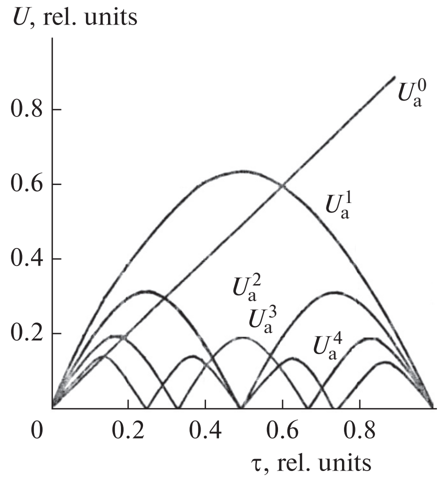

Fig. 3. Change in harmonic components of voltage on VM armature depending on duty cycle of PWR pulses.

$$i_a(t) = \sum_{S=-\infty}^{\infty}\sum_{r=1}^{\infty} I_a^{r,S} e^{j(r\Omega+S\theta)t}. \quad (2)$$

For the case of a trapezoidal law of change in the field in the gap, taking into account only the constant voltage component, the current in the armature winding will be

$$i_a(t) = \sum_{S=-\infty}^{\infty}\sum_{n=1}^{\infty} I_{a,n}^{S} e^{jS\theta t}.$$

Using the system of equations [4], one can write the current in the form

$$i_a(t) = \sum_{S=-\infty}^{\infty}\sum_{n=1}^{\infty} I_{a,n}^{S,r} e^{j(r\Omega+S\theta)t}. \quad (3)$$

Finally, the expression for the armature current will be the sum of solutions of type (3) for all harmonics of the applied voltage of type (1):

$$i_a(t) = \sum_{S=-\infty}^{\infty}\sum_{n=1}^{\infty}\sum_{r=1}^{\infty} I_{a,n}^{S,r} e^{j(r\Omega+S\theta)t}. \quad (4)$$

Determination of the amplitudes of the armature currents, both at sinusoidal and at trapezoidal distribution of induction in the air gap, must be carried out separately for each component of the applied voltage. When substituting the current in form (2) and (4) into the equilibrium equation [3], the equations are obtained, each of which breaks down into r systems of algebraic equations of arbitrary order. The solution of any of the systems is carried out similarly to the solutions described in [3, 4] for various laws of induction distribution in the gap.

The currents flowing through the armature winding will then be determined further as the sum of partial solutions for each rth harmonic of the applied voltage.

In PWR systems, switching frequency Ω is selected to be, as a rule, significantly higher than the maximum motor speed. Therefore, at sufficiently large value of U_a^0, the harmonic components of the armature current caused by alternating voltages $U_a^n e^{j(n\Omega t+\varphi_n)}$ (where n = 1, 3, 5, ...∞) are negligible in comparison with constant component of the armature current I_a^0 and their influence on the motor performance is negligible.

During the regulation process, a decrease in U_a^0 will entail a corresponding decrease in I_a^0, while the magnitudes of variable components of the current may increase.

Constant component U_a^0 causes in a motor armature, as has been shown, a current of the form

$$i_a = I_a^0 + \sum_{S=1}^{\infty} I_a^S \cos(k\theta t + \phi_a^S).$$

At the same time, the first harmonic U_a^0 will cause a current oscillation of corresponding frequency Ω; that is,

$$i_a = I_a^1 \cos(\Omega t + \varphi_1), \quad (5)$$

which should be one of the partial solutions of the system of differential equations [3], if the right side of this system is a periodic function of form (1) and, taking it into account that the mutual inductance along the d axis can be written as

$$M^d(\omega t) = M_0^d + M_k^{d^{\cos}} \sum_{k=1}^{\infty} \cos(k\theta t + \phi^k)$$

and the excitation current i_f in the first approximation is considered ideally smoothed, we obtain

$$\Omega M_0^d I_a \cos\left(\Omega t + \varphi_1 + \frac{\pi}{2}\right) + 0.5 I_a \sum_{k=1}^{\infty} (k\theta + \Omega) M_k^{d^{\cos}} \times \cos\left[(k\theta + \Omega)t + \varphi^k + \frac{\pi}{2}\right] + 0.5 I_a \times \sum_{k=1}^{\infty} (k\theta - \Omega) M_k^{d^{\cos}} \cos\left[(k\theta - \Omega)t - \varphi^k + \frac{\pi}{2}\right] + i_f R_f = U_f,$$

where

$$M_0^d = \frac{m}{\pi} M_m \sin\frac{\pi}{m} \cos\beta_0;$$
$$M_k^{d^{\cos}} = \frac{2m}{\pi} M_m \sin\left(\frac{\pi}{m}\right) \cos\beta_0 \frac{1}{4m^2k^2 - 1}. \quad (6)$$

Since the determination of current amplitudes $I_{a,f}^{s,k,n}$ must be made separately for each component of the applied voltage, when solving a system of differential equations, it breaks down into N systems of algebraic equations of arbitrary order [4], having the form

$$
\begin{gathered}
\left[0.5(\Omega+S\theta)\sum_{k=1}^{\infty}\overset{*}{L}_k-0.5j\sum_{k=1}^{\infty}\dot{X}_{L.k}\right]\dot{I}_a^{(S-k)}+\left[0.5(\Omega+S\theta)\sum_{k=1}^{\infty}\dot{M}_k-0.5j\sum_{k=1}^{\infty}\dot{X}_{M.k}\right]\dot{I}_f^{(S-k)}\\
+\left[j(\Omega+S\theta)L_0+X_{L0}+R_a\right]\dot{I}_a^S+\left[j(\Omega+S\theta)M_0+X_{M0}\right]\dot{I}_f^S\\
+\left[-0.5(\Omega+S\theta)\sum_{k=1}^{\infty}\overset{*}{L}_k+0.5j\sum_{k=1}^{\infty}\overset{*}{X}_{L,k}\right]\dot{I}_a^{(S+k)}+\left[-0.5(\Omega+S\theta)\sum_{k=1}^{\infty}\overset{*}{M}_k+0.5j\sum_{k=1}^{\infty}\overset{*}{X}_{M,k}\right]\dot{I}_f^{(S+k)}\\
=\dot{U}_a(n,S),\\
\left[0.5(\Omega+S\theta)\sum_{k=1}^{\infty}\overset{*}{M}_k-0.5j\sum_{k=1}^{\infty}\dot{X}_{M,k}\right]\dot{I}^{(S-k)}+j(\Omega+S\theta)M_0I_a^S+\left[j(\Omega+S\theta)L_f+R_f\right]\dot{I}_f^S\\
+\left[-0.5(\Omega+S\theta)\overset{*}{M}_k+0.5j\sum_{k=1}^{\infty}\overset{*}{X}_{M,k}\right]\dot{I}_a^{(S+k)}=U_f(S),
\end{gathered}
\tag{7}
$$

where at

$$
\begin{aligned}
\dot{U}_a(n,S)&=U^ne^{j\varphi_n} && S=0;\\
\dot{U}_a(n,S)&=0 && S\neq 0;\\
U_f(S)&=U_f^0 && S=0;\\
\dot{U}_f(S)&=0 && S\neq 0.
\end{aligned}
$$

$$
\begin{aligned}
&\dot{L}_k=0.5\left(L_k^{\cos}-jL_k^{\sin}\right); && L_k^{\cos}=\frac{m}{\pi}2\cos^2\frac{\pi}{2m}\left(L_d-L_q\right)\sin\frac{\pi}{m}\cos 2\beta_0\frac{1}{m^2k^2-1};\\
&\overset{*}{L}_k=0.5\left(L_k^{\cos}+jL_k^{\sin}\right); && L_k^{\sin}=\frac{m}{\pi}2\cos^2\frac{\pi}{2m}\left(L_d-L_q\right)\sin\frac{\pi}{m}\sin 2\beta_0\frac{mk}{m^2k^2-1};\\
&\dot{M}_k=0.5\left(M_k^{\cos}-jM_k^{\sin}\right); && M_k^{\cos}=\frac{2m}{\pi}M_m\sin\frac{\pi}{m}\sin\beta_0\frac{1}{4m^2k^2-1};\\
&\overset{*}{M}_k=0.5\left(M_k^{\cos}+jM_k^{\sin}\right); && M_k^{\sin}=\frac{2m}{\pi}M_m\sin\frac{\pi}{m}\cos\beta_0\frac{2mk}{4m^2k^2-1};\\
&L_0=\frac{m}{\pi}2\cos^2\frac{\pi}{2m}\left(L_d-L_q\right)\sin\frac{\pi}{m}\cos 2\beta_0; && M_0=\frac{2m}{\pi}M_m\sin\frac{\pi}{m}\sin\beta_0;\\
&\chi_{L_0}=\omega\frac{m}{\pi}2\cos^2\frac{\pi}{2m}\left(L_d-L_q\right)\sin\frac{\pi}{m}\sin 2\beta_0; && \chi_{M_0}=\omega\frac{2m}{\pi}M_m\sin\frac{\pi}{m}\cos\beta_0;\\
&\dot{\chi}_{L,k}=0.5\left(\chi_{L,k}^{\cos}-j\chi_{L,k}^{\sin}\right); && \chi_{L,k}^{\cos}=\omega\frac{m}{\pi}2\cos^2\frac{\pi}{2m}\left(L_d-L_q\right)\sin\frac{\pi}{m}\sin 2\beta_0\frac{1}{m^2k^2-1};\\
&\overset{*}{\chi}_{L,k}=0.5\left(\chi_{L,k}^{\cos}+j\chi_{L,k}^{\sin}\right); && \chi_{L,k}^{\sin}=\omega\frac{m}{\pi}2\cos^2\frac{\pi}{2m}\left(L_d-L_q\right)\sin\frac{\pi}{m}\cos 2\beta_0\frac{mk}{m^2k^2-1};\\
&\dot{\chi}_{M,k}=0.5\left(\chi_{M,k}^{a,\cos}-j\chi_{M,k}^{a,\sin}\right); && \chi_{M,k}^{\cos}=\omega\frac{2m}{\pi}M_m\sin\frac{\pi}{m}\cos\beta_0\frac{1}{4m^2k^2-1};\\
&\overset{*}{\chi}_{M,k}=0.5\left(\chi_{M,k}^{a,\cos}+j\chi_{M,k}^{a,\sin}\right), && \chi_{M,k}^{a^{\sin}}=\omega\frac{2m}{\pi}M_m\sin\frac{\pi}{m}\sin\beta_0\frac{2mk}{4m^2k^2-1}.
\end{aligned}
$$

Number n of these systems of equations of arbitrary order is determined by the given accuracy of determining the armature and excitation currents and the order of their decrease.

To determine the descending order of the harmonic components of currents $I_a^{n_1S}$, $I_f^{n_1S}$ and the required number of equations, one can use analytical expressions for currents at the zero ($S = 0$) approximation of the solution of the selected determinants, since it is the zero components of the periodic coefficients that are decisive when solving systems of arbitrary order of this type.

Thus, at $S = 0$, we obtain

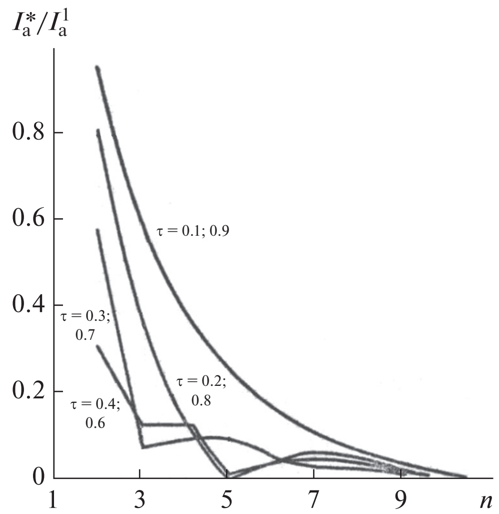

Fig. 4. Relative amplitudes of higher current harmonics at different duty cycles of width-modulated signal.

$$(j\Omega L_0 + X_{L0} + R_a)\dot{I}_a^{n,0} + (j\Omega M_0 + X_{M0})I_f^{n,0} = \dot{U}_a(n),$$
$$j\Omega M_0 I_a^{n,0} + (j\Omega L_f + R_f)\dot{I}_f^{n,0} = U_f(0).$$

As for the armature circuit, taking into account the above and taking (5) into account, for variable components, I_a^n can be written as

$$I_a^n = (-1)^n \frac{2U_a \sin n\pi\tau}{n\pi(jn\Omega L_0 + X_L^0 + R_a}. \quad (8)$$

Analysis of the resulting expression (8) shows that, with increasing number n, the nature of the decrease in the harmonic components of the current is quite complex and ambiguous for different angles of regulation of the duty cycle of the pulse-width signal τ.

The dependence of the higher harmonics relative to the first harmonic of the current presented in Fig. 4 shows that at certain values of the duty cycle τ, some harmonics of a higher order take on the values exceeding the value of harmonics of a lower order. Consequently, the series, the coefficients of which are determined by expression (8), has poor convergence, which does not allow one to simply evaluate the possibility of its truncation.

Analysis of these curves shows that at significant loads on the motor shaft, both the first and higher current components have a relatively small value throughout the entire range of changes in τ, if $\xi > 8$.

When $n = 0$, expressions for constant components of the currents I_a^0, I_f^0 are similar to the expressions obtained in [4], and the value of the armature voltage is determined by the duty cycle of the control pulses τ.

For each n different from zero, the harmonic components of the currents can be approximately determined by noting the following.

Since voltage on the inductor U_j does not contain alternating components, then, when $n \neq 0$, $U_f(n) = 0$. In addition, when the valve motor operates with angle $\beta = 0$, mutual inductance M_0, depending on the value of $\sin\beta$, is also zero. Therefore, the numerator of the second expression in (9) is absent, as a result of which the current in the excitation circuit is determined only by voltage U_f^0 and active resistance R_f and does not contain harmonic components.

Based on this, the components of the armature and excitation currents during pulse-width regulation of the voltage on the VM armature, taking into account the principle of position-dependent control of the valve switch, are determined by the following expressions:

$$I_a^n = \frac{U_a(n)(jn\Omega L_f + R_f) + U_f(0)(jn\Omega M_0 + X_{M0})}{(jn\Omega L_0 + X_{L0} + R_a)\times(jn\Omega L_f + R_f) - jn\Omega M_0(jnM_0 + X_{M0})},$$
$$I_f^n = \frac{U_f(0)(jn\Omega L_0 + X_0 + R_a) - U_a(n)jn\Omega M_0}{(jn\Omega L_0 + X_{L0} + R_a)\times(jn\Omega L_f + R_f) - jn\Omega M_0(jnM_0 + X_{M0})}. \quad (9)$$

However, the magnitude of the variable components of the armature current also largely depends on switching frequency Ω, and, at sufficiently high switching frequencies Ω, high harmonic currents become negligible relative to the constant component.

The nature of the change in the first harmonic armature current depending on the multiplicity of switching frequency to the motor speed ξ for different values of the duty cycle τ and loads on the motor shaft is shown, respectively, in Fig. 5.

If the motor load is small, neglecting the first harmonic can no longer be acceptable even at $\xi = 10$ (Fig. 5), and this harmonic has the greatest value at $\tau = 0.5$, which is due to the maximum value of the first harmonic of the applied voltage (Fig. 3).

The second and subsequent harmonics become insignificant at $\xi > 8$ throughout the entire range of changes in load and regulation parameter τ (Fig. 6).

Thus, if the switching frequency at PWR is an order of magnitude higher than the motor speed, in the nominal mode of operation of the engine, only the dc component of the applied voltage can be taken into account. However, when shedding the load, taking into account only the constant component may be

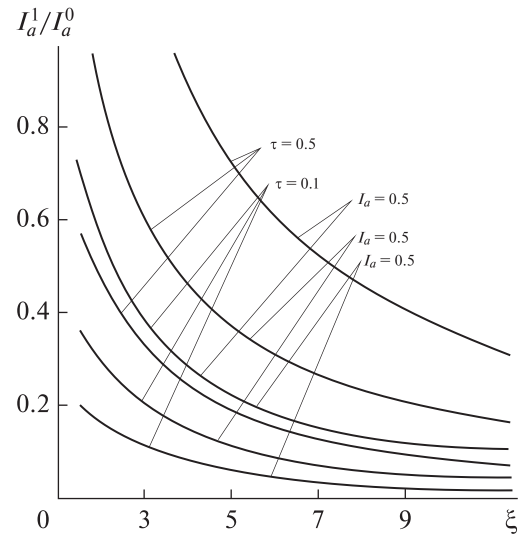

Fig. 5. Dependence of amplitude of first harmonic of current I_a^1 relative to constant component at different duty cycles and VM loads.

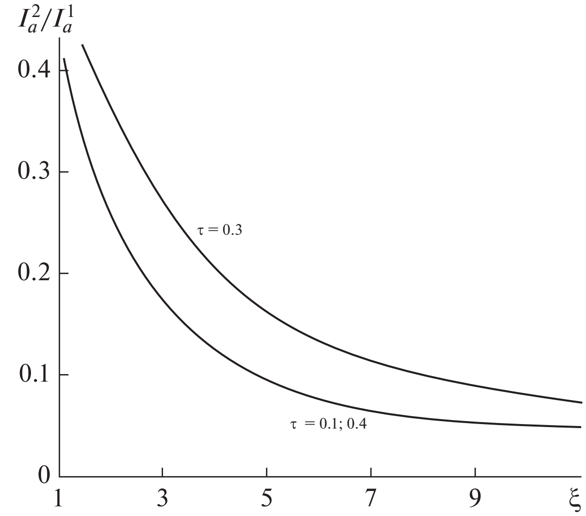

Fig. 6. Dependence of relative amplitude of second harmonic current on switching frequency factor for different duty cycles ($I_a^0 = 0.51 I_{a\ \mathrm{nom}}$).

insufficient, and in this case, the first harmonic of the alternating voltage should also be taken into account, especially since, in the control range at $\tau = 0.5$, the amplitude value of the first harmonic of the current can reach 30% of the constant component.

Consequently, when solving system of differential equations (7), it breaks down into two systems of algebraic equations of arbitrary order, from which the complex amplitudes of the components of the armature and excitation current can be determined.

Moreover, one of these systems allows determining the current components of frequencies $S\theta$, caused by the constant voltage on the armature, and the second allows determining the components of the current of combination frequencies ($\Omega \pm S\theta$) caused by the first harmonic of the supply voltage.

One of the most important points in solving the second system of equations is the determination of the components of infra-low-frequency currents that appear when switching frequency Ω is close to $S\theta$ and cause "oscillations" of the motor.

In this regard, the following can be noted. The greatest likelihood of "swinging" occurs at low motor loads, when the rotation speed is higher than in the nominal mode. This situation is explained by the fact that the equality of frequencies Ω and $S\theta$, for high rotation frequencies, occurs at lower S, and, since the higher harmonic ones decrease in proportion to S, the currents and, accordingly, the component of the torque of the infralow frequencies have high value at high speeds.

Obviously, in the process of regulation over a wide range of change in the speed, "swings" appear for several discrete values of τ. However, their magnitude can be so insignificant that, due to the inertia of the rotor, they will have practically no effect on the operation of the motor. Moreover, the higher switching frequency Ω, the less the magnitude of components of current and torque of infralow frequencies. Since an excessive increase in Ω leads to an increase in losses and, accordingly, its dimensions, the question of determining the minimum switching frequency at sufficiently small torque components of infralow frequencies is very important and must be solved specifically for each standard size of the VM, based on the specified control range, moment of resistance on the shaft, and design parameters and characteristics.

Calculation of the components of the electromagnetic torque for a VM prototype showed that the highest value of the torque of combination frequencies $M_{\mathrm{EM}}^{\mathrm{CF}}$ occurs within the range from 0.5 U_a^0 to 0.7 U_a^0 and is determined mainly by the first harmonic of the alternating voltage (Fig. 7).

Some shift to the right of the maximum value of $M_{\mathrm{EM}}^{\mathrm{CF}}$ relative to $0.5U_a^0$ is explained by the slight influence of the second component of the harmonic voltage on the armature.

It should be noted that the magnitude of the components of the torque of combination frequencies is negligible throughout the entire control range τ if the ratio of the switching frequency to the motor rotation speed is more than 10 (Fig. 7).

At a lower multiplicity, the components of the torque can cause already noticeable "swings" in the motor operation, since, for example, at a multiplicity of 7, this component reaches 12–15% of the rated torque.

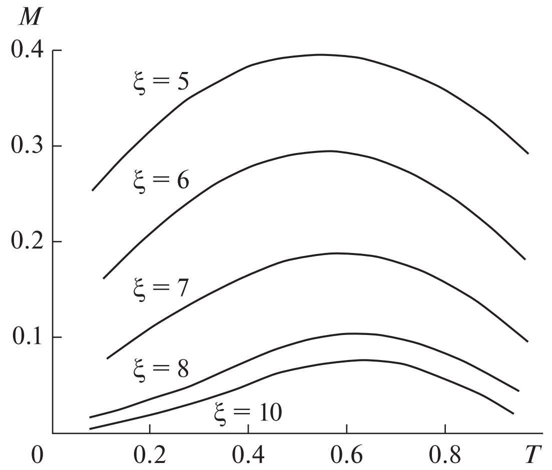

Fig.7. Dependence of moment of combination frequencies on duty cycle.

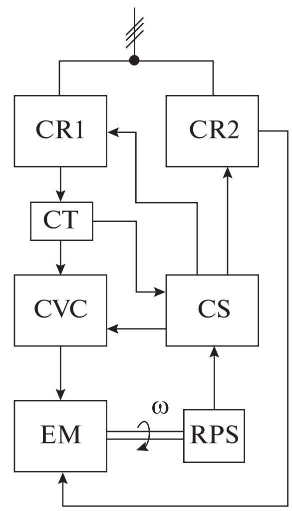

Fig. 8. Functional diagram of VM.

The functional diagram of an electric drive with a VM includes a synchronous machine with electromagnetic excitation—an electromechanical part (EM); rotor-position sensors (RPSs); a valve converter with position-dependent commutation (CVC), a control system (CS) (Fig. 8), which determines the operating modes of the motor; two controlled rectifiers (CR1 and CR2), one of which provides regulated power to the armature circuit, and the other to the field windings; and current transducers (CTs) designed for protection against overload and short circuits in a VM and CVC.

The three-phase armature winding of a synchronous machine, connected in a star, is located, as usual, on the stator. The inductor is a salient-pole rotor, and voltage is supplied to its winding through slip rings.

The functional diagram of a wide-adjustable electric drive with a VM is shown in Fig. 8, and technical data on the electromechanical part—a salient-pole synchronous machine with electromagnetic excitation—in Table 1.

Under PWR of voltage on the armature winding in the case of using permanent magnets, there are some features that contrast with a VM with electromagnetic excitation.

When a field is created by permanent magnets (according to (2) and (4)), the current frequencies under PWR are only multiples of ($Sk\theta + r\Omega$); that is, in the current spectrum of the armature there are no combinational components that are multiples of Sk, as well as $r\Omega$.

Table 1. Basic technical data of an EM VM

*P*n	*U*ph	*I*ph	*m*	*If*	*R*ph	*Rf*	*Ld*/*Lq*	2*p*
4.5 kW	220 V	11.3 A	3	11.3	0.76 Ω	2.28 Ω	1.38	4

Thus, the replacement of the excitation winding with permanent magnets leads to an improvement in the harmonic composition of the armature current curve at PWR. However, a significant increase in the switching frequency, Ω, i.e., the carrier frequency of PWR, entails an increase in losses in the converter and, as a consequence, an increase in the mass and dimensions of the cooling radiators of CVC power switches.

CONCLUSIONS

Thus, under PWR, the valve motor has regulating characteristics similar to the commutator motor with armature control, and variable components of the electromagnetic moment of frequencies ($S\theta \pm n\Omega$) at sufficiently high switching frequency factor ($\xi \geq 10$) do not have a significant impact on the motor operation.

In a VM with electromagnetic excitation, transformer EMFs appear in the excitation circuit of the frequency $Sk\theta \pm r\Omega$, under the influence of which EMFs arise in the armature circuit and currents of the frequency, as well as a multiple of $Sk\theta \pm r\Omega$.

ABBREVIATIONS AND NOTATION

DC	direct current
VM	valve motor
CVC	controlled valve switch
ω	rotational speed
PWR	pulse-width regulation
Ω	frequency of fundamental harmonic of alternating voltage component
τ	duty cycle of control pulses
ξ	switching frequency factor to main rotation speed.
β	angle
cp	control pulse

U_f^0	voltage
Rf	active resistance
CF	combination frequency
EM	electromechanical part
RPS	rotor-position sensor
CS	control system
CR	controlled rectifiers
CT	current transducer

FUNDING

This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. Lebedev, N.I., Gandshu, V.M., Yavdoshak, Ya.I., et al., *Ventilnie elektricheskie-mashiny (Valve Electric Machines)*, Glebov, I.A., Ed., St. Petersburg: Nauka, 1996.
2. Konstantinov, V.G. and Krylov, V.S., Thyratron motors with analog and digital control systems for the electric drives of autonomous objects, *Russ. Electr. Eng.*, 1996, vol. 67, no. 5, pp. 39–51.
3. Vysotsky, V.E., Valve motors-generators for electric power complexes of autonomous objects, *Materialy Vserossiyskoy nauchno-tekhnicheskoy konferentsii. Problemy Elektrotekhniki i Elektroenergetiki* (Proc. All-Russian Sci. and Tech. Conf.: Problems of Electrical Engineering and Electric Power), Tolyatti: Tol'yattinsk. Gos. Univ., 2004, pp. 60–64.
4. Vysotsky, V.E., *Matematicheskoe modelirovanie ventil'nih dvigateley s iskusstvennoy kommutatsiey* (Mathematical Modeling of Valve Motors with Artificial Switching), Samara: Samarsk. Gos. Tekh. Univ., 2004.

Translated by Sh. Galyaltdinov