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Experimental study of the VFD's speed stabilization processes under torque disturbances

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ABSTRACT

Maintaining speed with various jumps and changes in load torque is one of the main tasks of variable frequency drives (VFD). The article considers the operation of the VFD under the influence of periodic perturbations of variable frequency and amplitude. The dependence of the transient function of the VFD and the family of frequency characteristics associated with it on the frequency of the stator voltage and slip underlies the methodology for experimental studies of such drives. The traditional method is based on the response to harmonic stimulation and works well for a non-linear system. In the course of the work, it was found that the introduction of dynamic positive feedback (DPF) allows to compensate for disturbances of varying frequency and amplitude. Experiments with a sinusoidal change in the load torque have shown the effectiveness of introducing the DPF in front of conventional sensorless control systems (vector and scalar).

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1. INTRODUCTION

One of the important tasks of variable frequency drives (VFD) is to maintain a constant value corresponding to the speed reference signal during surges and variations in load torques [1]–[3]. To fend off these indignations, keeping the rotation speed at the required level is quite difficult. The most important reason for this is the description of variable frequency drives used in control algorithms by vector equations, diagrams and equivalent circuits of AC motor [4]–[6]. Such techniques are principally suitable only for describing static modes. The fallacy of these methods is especially evident in the study of modes of parrying torque loads. A number of technical difficulties follow from this:

– Speed reduction with increasing load torque for induction motors (IM). For general industrial motors, the nominal slip is in the range of 4-10% [7]–[12]. However, according to technological requirements for most modern mechanisms, the deviation in speed should not exceed 1%.
– Asynchronous electric drives with speed feedback have a dynamic dip, which can reach 10-15%. Such a failure is typical even for vector control systems. It is almost impossible to eliminate this shortcoming using the PID controller [13]–[18] used in frequency converters.
– The presence of non-linear elements in the VFD (frequency converter, induction motor, reducer) [19]–[22] significantly complicates the process of setting the parameters of the PID controller, and therefore determines the magnitude of the speed deviation during load surge. Magnetic saturation in the electric motor, impulse elements in the frequency converter, the presence in the real mechanism of gaps,

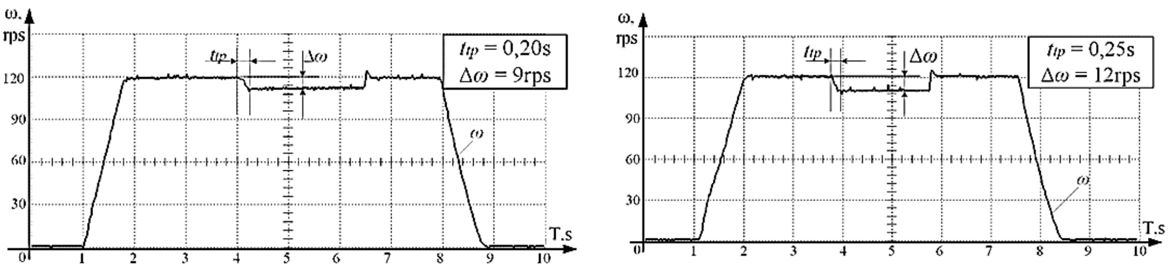
backlashes that change during the operation of the elements, lead to the appearance of voltages and currents of various harmonics, which reduce the developed torque, because as well as time delays that cannot be completely eliminated by complicating the automatic control system.

The presence of the above problems explains the difficulties in determining an appropriate VFD control system. As a result, engineers choose modern vector control systems (VCS), which are considered the most effective for controlling the speed of IM compared to scalar control systems (SCS). In this case, the most important research tool becomes experiment and its methodology, which takes into account the nonlinear continuous characteristics of drives.

2. PROBLEM DEFINITION

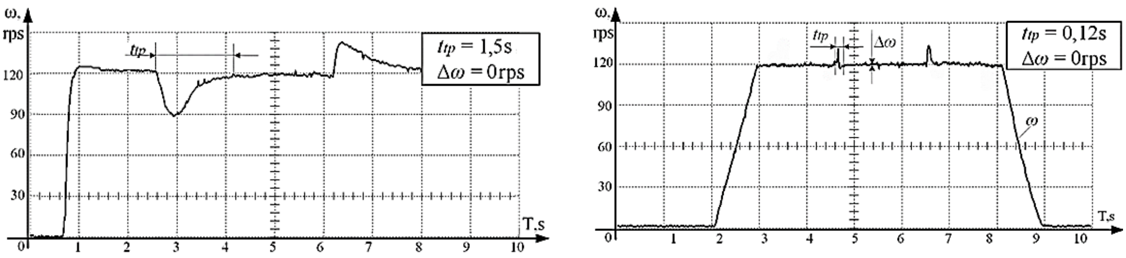
The traditional method for assessing the quality of rotation speed stabilization is experiments with a stepwise change in the load torque [23]–[26]. The processes of parrying surges of “stepwise” load in a drive with VCS shown in Figure 1(a) have no significant advantages over processes in a drive with SCS as shown in Figure 1(b)), neither the time of the transient process, nor the value of the “drawdown” of the rotation speed. A closed-speed vector control drive has zero static speed error, but the transient has significant dynamic dip and long recovery time in Figure 2(a). A drive with dynamic positive torque feedback (active component of the stator current) has higher rates of speed stabilization and load parrying in Figure 2(b). The operation of such control is described in detail in the [26]–[28].

The problems are complicated by the fact that the vector equations describing the VFD fundamentally do not take into account the variations in the load torques [29]–[31]. Based on vector equations and equivalent circuits, it is quite difficult to explain the experiments results and, moreover, to predict new results.



(a) (b)

Figure 1. Loading process in (a) VFD with sensor less vector and (b) scalar control



(a) (b)

Figure 2. Loading process in (a) VCS with speed feedback (b) and SCS with DPF

Kodkin *et al.* [32], for the interpretation of a nonlinear link that forms a torque in an IM, the concept of a nonlinear transfer function (NTF) is proposed. This function takes into account the change in the load through the value of the absolute slip, as well as the change in the frequency and amplitude of the stator supply voltage. It can describe the processes in the system for any input signals. This function has the following form:

$$W(p) = \frac{2M_k(T_2'p+1)S_k}{\omega_1[(1+T_2'p)^2S_k^2+\beta^2]}, \quad (1)$$

where, M_k – the critical torque, $T_2' = \frac{L_k}{R_2}$ – the transient time constant of the rotor, s_k – the critical slip at the nominal frequency ω_1, $\beta = \frac{\omega}{\omega_1}$ – the relative slip.

The (1) is a family of transfer functions, which in the theory of automatic control very clearly defines a family of frequency characteristics. These amplitude-frequency characteristics (AFC) describe the response of the control system to a harmonic input signal; an example of such a family for a link that forms a torque in a VFD is shown in Figure 3.

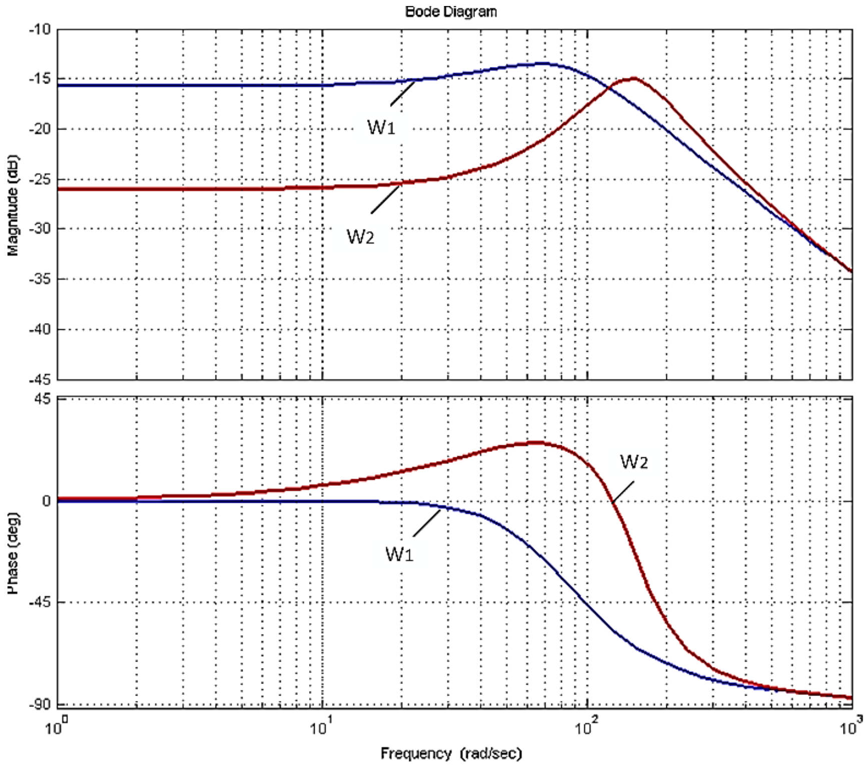


Figure 3. Frequency characteristics of IM at the frequency of supply voltage of 10 Hz and slip, corresponding to nominal (W2) and low (W1) torque of load

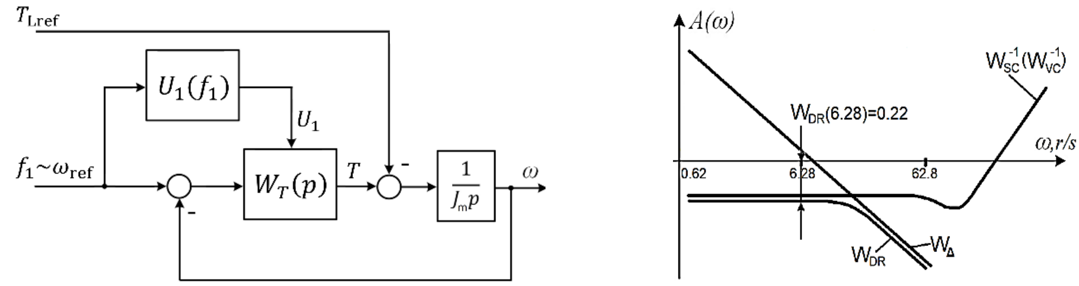
These frequency characteristics correspond to the transfer function, determined by (1), at *β = 10* and *β = 0%*, which corresponds a load torque close to the nominal and to zero. It can be seen from the figure that as the link grows, it tends to oscillate.

Various algorithms for controlling asynchronous motors "interact" with these frequency characteristics. The block diagram of a scalar control drive is shown in Figure 4(a). The first input signal is a speed reference signal ω_{ref} determined by the supply voltage frequency f_1. This signal is constant. The second input signal is the load torque reference signal T_{Lref}, the negative connection is formed by the structure of the formation of the torque. The task of the system is to completely suppress the input signal T_{Lref}, that is, to exclude the influence of the load torque on the rotation speed. The more efficient the formation of the torque in the drive, the less the influence of the load torque on the rotation speed.

AFC with the load torque input is shown in Figure 4(b). The link of the torque formation in the VFD with scalar control is located in the reverse channel, therefore the AFC W_{sc}^{-1} is built inverted. The transfer characteristic of the forward channel W_Δ represents the AFC of the integrating link. The resulting AFC of the drive W_{DR} is close to the characteristic of the inertial link with a weakened proportional region. This characteristic is constructed by the method of constructing the approximated frequency characteristics of closed loops by the forward and reverse frequency characteristics of the tails of the forward channel and feedback, respectively [14], [16].The characteristic W_{DR} generally corresponds to the process of parrying a stepped load torque in Figure 1(b).

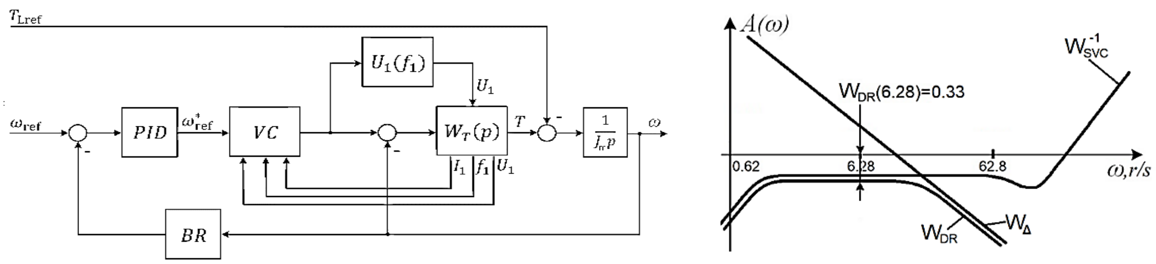
The vector control system, using the model embedded in it and the signals of the voltage amplitude on the stator, its frequency and stator current, should linearize the nonlinear connections in the VFD. But it is very difficult to do this by sequential correction without direct measurement of the speed, therefore the equivalent frequency characteristics of the drive W_{vc}^{-1} change little in comparison with scalar control in Figure 4(b), as well as the process of parrying the step load torque in Figure 1.

The vector control system with a speed regulator in Figure 5(a) is trying to exclude the action of counter EMF. With some error it is possible but parrying of the load torque occurs due to the external contour is very tightened in Figure 2(a). The AFC of the link of the torque formation with the vector control system with a PID controller W_{svc}^{-1} and of the drive W_{DR} correspond to this Figure 5(b).



(a) (b)

Figure 4. The drive with scalar control of (a) structural diagram and (b) AFC

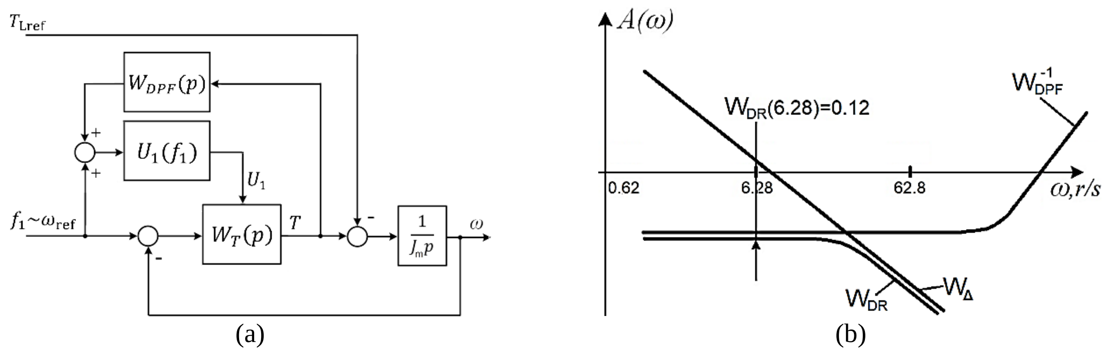


(a) (b)

Figure 5. The drive with vector control with speed feedback (a) structural diagram and (b) and AFC

It follows from the characteristic W_{DR} in Figure 5(b) that the integral channel of the regulator, which effectively suppresses the static error of the drive, does not come into operation at medium frequencies, so as not to worsen the stability of the system. Therefore, the process of parrying a step load is delayed, and parrying complex loads may be ineffective if the integral channel is not involved.

The proposed dynamic positive torque feedback (DPF) on electromagnetic torque [21] linearizes the drive, practically eliminating the dependence of the dynamics on the supply voltage frequency and significantly reducing the dependence on slip. The block diagram of such a system looks as follows in Figure 6(a), and the corresponding AFC are shown in Figure 6(b).



(a) (b)

Figure 6. the drive with scalar control with DPF on electromagnetic torque, (a) structural diagram and (b) AFC

From the AFC shown in Figure 4(b), Figure 5(b) and Figure 6(b), it follows that in the range of medium frequencies from 1 to 10 Hz (from 6.28 to 62.8 rps) vector control has no advantage in dynamics. Experiments on parrying step loads cannot in any way confirm or disprove this assumption. It is necessary to carry out studies with more complex perturbations that would most accurately reflect the dynamic properties of VFDs with one or another control algorithm. Such experiments are usually carried out for structures identified by transient functions and frequency characteristics. On their basis, it is possible to study the response of the drive to sinusoidal variations in the load torque with a frequency corresponding to changes in the load in the investigated mechanism.

3. EXPERIMENTAL RESEARCH

The scheme of the laboratory stand, on which the experimental studies were carried out, is shown in Figure 7. The load torque is set by the VFD UZ1-M1, to the input of which a sinusoidal signal of the investigated frequency is fed from the generator SG1. The UZ1 drive can operate in vector control mode. The investigated VFD UZ2-M2 receives a signal for setting the rotation speed from potentiometer R2. The UZ2-M2 drive tries to maintain this speed by counteracting the load torque from the loading motor M1. The better it is, the smaller the amplitude of the sinusoid of the speed change of M2.

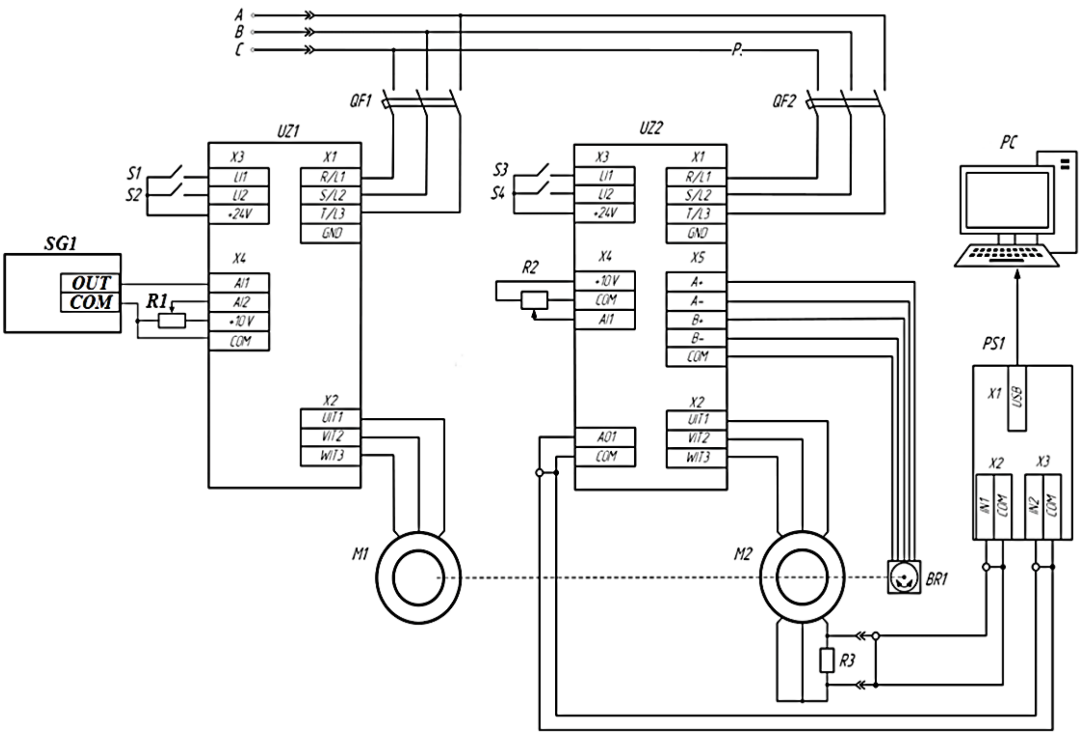


Figure 7. The scheme of the laboratory stand UZ1, UZ2–frequency converter; SG1-signal generator; BR encoder; M1–load motor; M2–slip-ring IM; PS1–oscilloscope; PC–personal computer

The signal proportional to the rotation speed of the investigated drive *M2* is recorded from the speed sensor through the frequency converter *UZ2*. Evaluation of the efficiency of the VFD control algorithms, namely their ability to compensate for the decrease in speed when the load torque rises, can be performed by comparing the results of transient processes. To do this, it is necessary to compare the amplitude of the sinusoidal component of the speed output signal for different control systems, as well as the phase shift between the sinusoidal disturbance and the sinusoidal component of the speed output signal.

The experiments were carried out in the following sequence:

- 1 The induction motor M2 under study was supplied with a supply voltage with a frequency ranging from 10 to 50 Hz using a UZ2 frequency converter.

– 2 To the analog input of the frequency converter UZ1, which sets the torque of the motor M1, a harmonic signal is supplied from the generator SG1. Thus, a sinusoidal load torque is formed. The frequency of the load torque varies from 0 to 5 Hz, and the amplitude of the load torque slightly changes the transfer function (1) in the parameter β.
– 3 For each speed of rotation of the motor M2, determined by the frequency of the supply voltage, a signal corresponding to it is recorded. This speed signal has a constant component, determined by the frequency of the supply voltage, and a sinusoidal component, determined by the disturbance. Therefore, by comparison, it is possible to compare the sinusoidal component with the load torque reference signal.

Based on the theory of automatic control, it turns out that the ability of the VFD to stabilize the speed under complex disturbances is the better, the smaller the phase shift between the sinusoidal component of the speed signal and the load torque setting signal, and also the smaller the amplitude of the sinusoidal component of the speed signal. That the lower these two parameters, the more efficient the VFD control system. An example of the analysis of the efficiency of the VFD is shown in Figure 8. The M2 motor runs at a speed corresponding to the supply voltage frequency of 30 Hz. A reference frequency signal of 1 Hz is fed to the analog input of the frequency converter UZ1. The response to such a load torque by various control systems of the UZ1 converter is shown in Figure 8(a), Figure 8(b) and Figure 8(c). An example for a frequency of 1 Hz is shown in Figure 8. The reference signal Figure 8(d) generates a sinusoidal disturbing torque on the load motor. The responses of the VFD with different control systems to this disturbance are shown in Figure 8(a), Figure 8(b) and Figure 8(c).

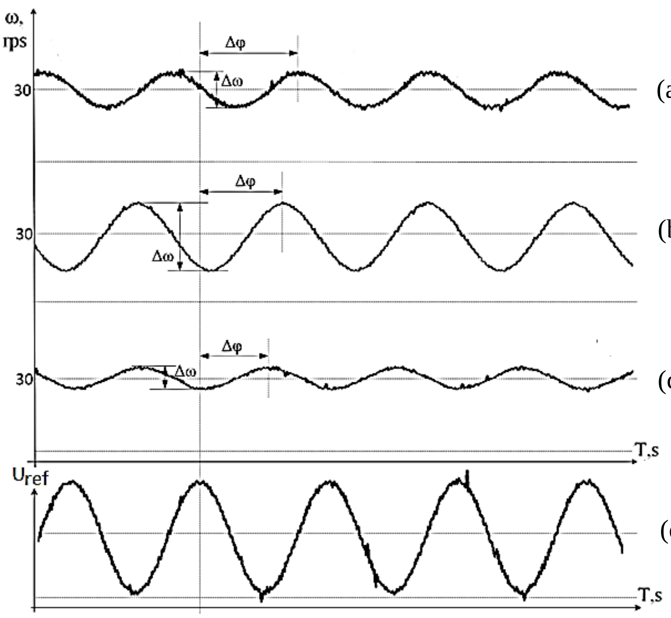


Figure 8. The results of evaluating the effectiveness of various VFD control algorithms (a) sensorless system (SCS and VCS), (b) VCS with speed feedback, (c) SCS with DPF on electromagnetic torque, and (d) load torque reference signal

4. ANALYSIS OF EXPERIMENTAL RESULTS

The magnitudes of the amplitudes of the sinusoidal components of the speed signals and their phase shifts relative to the disturbing signal, depending on the PFD control system, are presented in Table 1. Based on the experimental results shown in Figure 8 and Table 1, it can be seen that the VCS with speed feedback under dynamic load shows the maximum amplitude of the sinusoidal component of the speed signal of 3.2 rad/s is in Figure 8(b). Traditional systems of sensorless control of the VFD (SCS and VCS) showed close results of load parrying. The amplitude of the sinusoidal component of the speed signal in Figure 8(a) is in the region of 2.2 rad/s. The scalar system with DPF has the best performance. The amplitude of the sinusoidal component of the speed signal in Figure 8 is 1.2 rad/s.

The proposed technique eliminates the need to calculate the frequency characteristics of the required VFD, which is a difficult task. It is enough to change the frequency of the sinusoidal disturbing action and control the amplitude of the sinusoidal component of the speed signal and its phase shift relative to the disturbing signal. This will make it possible to compare the effectiveness of different control algorithms at different points in the frequency domain.

Detailed experimental results for a rotation speed corresponding to a stator voltage frequency of 30 Hz are shown in Table 1. In this case, the frequency of the harmonic interference signal was 1 Hz. Studies have also been carried out for rotational speeds corresponding to frequency of supply voltage from 10 to 50 Hz and interference frequencies up to 5 Hz. However, they differ little from the results presented in Table 1.

Table 1. The results of evaluating the effectiveness of various VFD control algorithms

Control system type	Δω, rad/s	Δφ, el. Deg
Open loop system	±2.2	270
Speed feedback system	±3.2	230
System with DPF on electromagnetic torque	±1.2	200

5. CONCLUSION

The proposed method for identifying the dynamic characteristics of the VFD by applying a sinusoidal load torque is a fairly effective tool. It has a high "sensitivity" because allows you to determine the parameters in a significant range of the frequency domain. Comparison of these parameters makes it possible to choose the most efficient VFD control system depending on the type of the load torque, solve the given task. The description of the IM torque formation link by the NTF has sufficient accuracy for calculations when the supply voltage frequency changes from 0 to 50 Hz. SCS with DPF by electromagnetic torque is characterized by the best ability to suppress variable disturbances of low frequencies in comparison with sensorless SCS and VCS. This system showed the minimum values of the amplitude of the sinusoidal component of the speed signal and its phase shift relative to the disturbing signal, the frequency of which varied from 0 to 5 Hz. It turns out that the DPF linearizes the VFD and mainly the NTF of the IM torque formation link in the supply voltage frequency range from 0 to 50 Hz.

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