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IMPROVEMENT OF THE QUALITY OF CONTROL OF THE ELECTRIC DRIVES WITH INDIRECT SPEED MEASUREMENT

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ПІДВИЩЕННЯ ЯКОСТІ РЕГУЛЮВАННЯ ЕЛЕКТРОПРИВОДІВ З НЕПРЯМИМ ВИМІРЮВАННЯМ ШВИДКОСТІ

Purpose. Generalization of the results of studies of the electric drive features with indirect speed measuring associated with the presence of the positive current feedback, with the significant voltage feedback pulsations in DC motor, with display of instability of the induction motor, and consideration of their practical use to improve the control quality.

Methodology. The methods for improving of the control quality through: full compensation of droop mechanical characteristics of the motor at a certain average temperature of the windings with the assumption of overcompensation by the temperature changes; reducing of the inertia of the voltage sensor by a digital smoothing its signal in the microprocessor control system in DC drive; sustain of stability of the induction motor in AC drive.

Findings. Defined the fields of stability of control system at positive current feedback in DC drive and at active current feedback in asynchronous electric drive. Defined the fields of stability of control loop with thyristor converter at digital smoothing of feedback signal. Defined the fields of stability of the induction motor as a function of the coefficient of the magnetic flux scattering, electromechanical time constant, time constants of the stator and rotor. Substantiated the control structures and system parameters that provide quality control of the electric drives.

Originality. Methods of choosing the parameters of the speed controller at the positive current feedback. Conditions of stability of control loop with thyristor converter at digital smoothing of feedback signal. Stability boundaries of the induction motor subject to the coefficient of the magnetic flux scattering, electromechanical time constant and the time constants of rotor and stator. Improvement of the control structures of electric drives with the indirect speed measuring.

Practical value. Implementation of the results of research in electric AC and DC drives produced by Zaporizhia Electrical Apparatus Plant and Science Research Institute of the Power Electronics.

Keywords: *electric drive, control system, stability, thyristor converter, induction motor*

Introduction. Expending of possibility of speed control of electric drives (ED) without speed sensors is an important scientific and practical task. Indirect speed measuring by calculating current and voltage encounters the problem of stability of circuit of compensation the static error of the speed control. In addition, the DC ED (DCED) has problem of stability of the voltage loop, in asynchronous ED (AED) arises the problems of stability of the induction motor (IM) and providing its stability without loss of static control accuracy.

Analysis of the studies. Compensation static error of the speed control with increasing of load of electric motor (EM) is realized by the positive feedback (FB) – on current in the DCED and on the active current in AED [1].

By increasing of the positive FB in DCED static error can be reduced to zero at a certain average value of the temperature EM with the assumption overcompensation of static error of the speed control (see under "overcompensation") with the temperature decreasing of ED resistance, so you can improve the static accuracy of control. If neglected the influence of FB on ED EMF which characterized electromechanical time constant T_M , then at full compensation of static error of the automation control system (ACS) is on the stability boundary. It is received an expression for the limit in terms of sustainability overcompensation that takes into account the influence FB on EMF [2]. Expression is obtained without account of inertia of the voltage sensor. Since the inertia of the voltage sensor can only worsen sustainability of ACS, in DCED invited to minimize it, to reduce the ripple of the voltage sensor output signal is proposed to use digital smoothing of this ripple by repeated reading the signal and its averaging over the period of converter discrete by microprocessor control system (MPCS). The above expression gives the possibility to choose the controller parameters by which the allowable amount of

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overcompensation of static error more then arising from temperature changes of the EM resistance.

However, the controller parameters are chosen based on the possible instability of the internal control loops.

In DCED while reducing of inertia of voltage sensor most critical to oscillations associated with the discrete of control of converter is voltage control loop. Conditions of stability at digital smoothing of FB signal [2] substantially restrict the voltage loop gain, which in turn limits the performance of the speed control.

IM considering FB of EMF is also a closed control loop, in which oscillations of current and speed can occur. The presence of positive FB of active current in AED with indirect speed measuring can contribute to the emergence of self-oscillation, which could not be shown at negative FB or in its absence. Investigating the stability of IM by method of frequency characteristics analysis in the linearization of differential equations system conducted A.A. Bulgakov, V. Lyon, I.I. Epshtein and other scientists, allow only qualitative to study the stability. Another method to study electromechanical self-oscillations arising in IM is the mathematical modeling of the complete system of differential equations of IM, which contain the products of variables. In this case the boundary of stability of IM was determined by multiple automatic sorting options of calculation using a special algorithm [2].

Among possible ways to suppress electromechanical self-oscillation mode is selected applying FB of reactive current component to the impact on the frequency *f*, as this does not degrade the speed control accuracy.

By maintaining by a constant rotor magnetic flux expression for the allowed value for overcompensation in DCED is true for AED, if processes are considered in relation to the active component of the stator current [2].

The purpose of this paper is to summarize the results of studies of stability of control system of drives with indirect speed measuring and consideration of their practical use.

Material and research results. ***Determination of the stability field of loop with thyristor converter at digital smoothing of FB signal.*** Availability of digital signal smoothing of FB distinguishes stability analysis of studies conducted by N.A. Beresten, V.P. Shipillo and other authors. Taking the period of discrete converters *T* constant, the transfer function of the digital filter can be represented as

$$G_{ф}(p) = (1-\exp(-pT))/\ \ p\,\cdot$$

As a result of the study of contour stability by *Z*-transform is defined the tolerance range of system gain *Kpu* in dependence on the time constant of the voltage sensor T_{VS}

$$K_{IU}\left(\frac{T_{VS}}{\mathrm{T}}-\frac{1}{\mathrm{e}^{\mathrm{T/T_{VS}}}-1}\right)<K_{pu}<\left(1-\frac{1}{2}\frac{T}{T_{\mathrm{int}}}\right)\frac{1+e^{-\mathrm{T/T}_{VS}}}{1-e^{-\mathrm{T/T_{VS}}}}+\frac{T_{VS}}{T_{\mathrm{int}}}, \quad (1)$$

where tint – integration time constant of circuit.

Stability boundaries of the control contour according to the expression (1) are shown in Fig. 1, the dashed lines indicate the boundaries of the known from works by V.P. Shipillo stability boundaries for thyristor converter (TC) controlled by methods PWM-I and PWM-II. From a comparison of the curves on Fig. 1 one can see, that the ACS with TC at digital smoothing of FB signal for stability occupies an intermediate position among the pointing known controled methods.

To improve speed regulation accuracy the coefficient K_{pu} required to increase, that is possible, as shown in Fig. 1, while increasing of the time constant of the voltage sensor T_{vs}. However, it deteriorates dynamics and reduces allowable value of overcompensation caused by temperature changes.

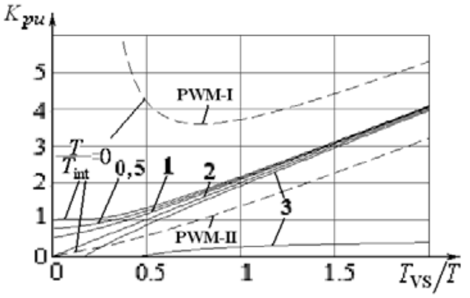


Fig. 1. Stability boundaries of ACS with TC at digital smoothing of feedback signal (in compared at the known methods of TC control PWM-I and PWM -II)

ACS stability at overcompensation of static error of the speed control. Structure of the most common single integrating ACS at indirect speed measuring (Fig. 2) contains: a control loop current *Id* with PI current controller CC, thyristor converter TC; EM armature circuit with a time constant T_A, resistance R_A; current sensor with parameter R_{CS}; voltage U_d sensor with parameters T_{VS}, K_{VS}; voltage controller VC with a coefficient K_U; current compensation circuit with coefficient K_{RU}. At constant of magnetic flux the speed *V* and the EMF *E* proportional to each other, E_{sv}, V_{sv} are set values of *E* and *V*. $I_{d.S}$ is steady-state current of EM. Dotted bond is not considered and it will be discussed further.

As noted above, a large inertia of voltage sensor reduces the possibility of full compensation with considering overcompensation at the temperature change of the resistance of EM. At the same time, low inertia of voltage sensor does not affect to the processes of the speed change. Taking $T_{VS} = 0$ and neglecting dickretion of TC, processes in the system can be described by a differential equation of the third degree, which allows to obtain the condition of the system stability in an analytical form. This condition is obtained with respect to the overcompensation coefficient *k*, which determines the relative difference between the calculated resistance of the motor circuit $R_{A..calc}$ for calculation of compensated voltage drop and the real resistance R_A , which depend on temperature changes

$$k = \left(R_{A.calc} - R_A\right)/R_A\,\cdot \quad (2)$$

Stability condition in speed ACS of has the form (3)

$$k < \frac{1 + K_{PU}\left(1 + K_{PU}\right)\frac{T_{\text{int}}}{T_M} + \frac{T_A}{T_{\text{int}}} - \sqrt{\left(1 + K_{PU}\left(1 + K_{PU}\right)\frac{T_{\text{int}}}{T_M} + \frac{T_A}{T_{\text{int}}}\right)^2 - 4K_{PU}\left(1 + K_{PU}\right)\frac{T_{\text{int}}}{T_M}}}{2K_{pu}}, \quad (3)$$

where $Tint = T / K_{IU}$ – integration time constant of the voltage loop; $K_{IU} = K_{VS}\, K_U K_I K_{TC}$, $K_{PU} = K_{VS}\, K_U K_P K_{TC}$ – gains of the open voltage loop with accountancy the integral K_I and proportional K_P parts of the controller. From this the total stability condition individual cases can be determined

$$k < \frac{T_{\text{int}}}{T_M\left(1 + \frac{T_A}{T_{\text{int}}}\right)}, \quad \text{for } K_{PU} = 0; \qquad (4)$$

$$k < 0 \text{ , for } T_{\text{int}}/T_M \to 0. \qquad (5)$$

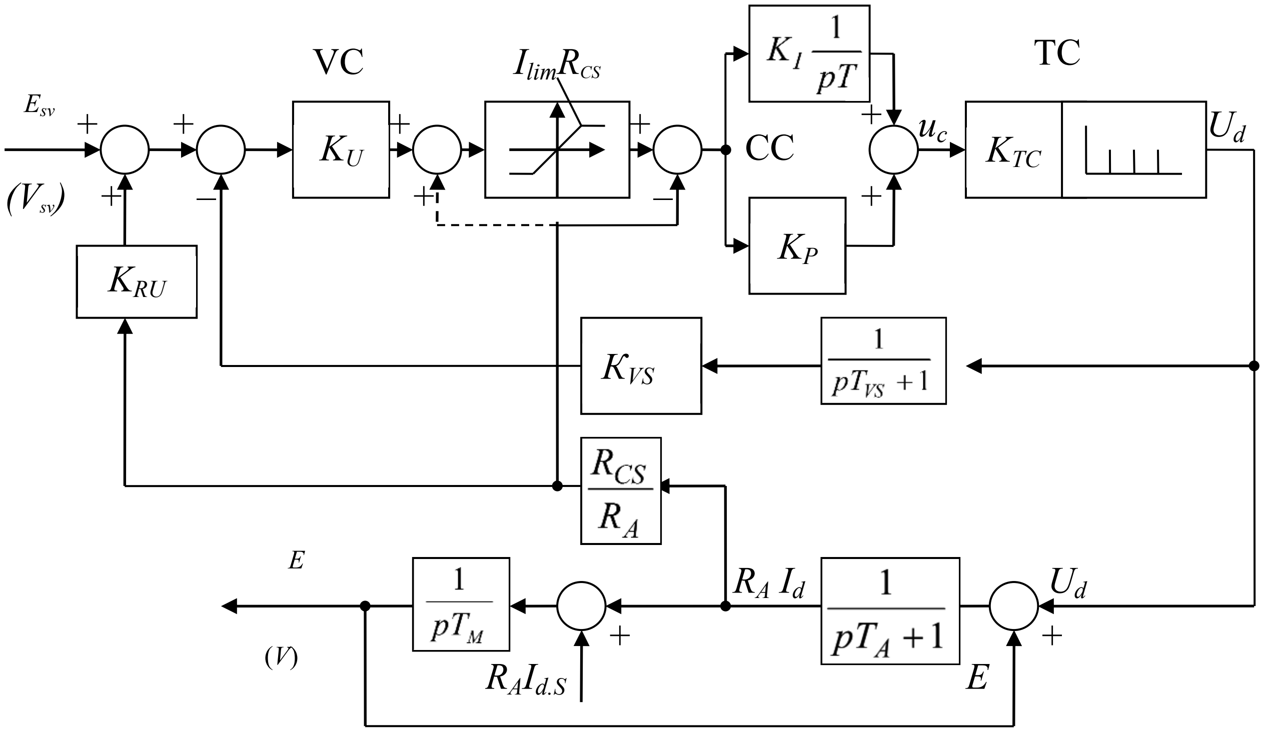


Fig. 2. Control structure of DCED with the indirect speed measuring

Stability condition (5) means that if you do not consider FB in motor EMF ($T_M \to \infty$), that is sometimes acceptable, then the system is unstable at full compensation and overcompensation is not allowed in general. In fact, thanks to the FB in motor EMF full compensation and overcompensation at temperature change can be provided. Expression (3), which accounted FB in EMF, allows selecting the appropriate of controller parameters under which a real possibility overcompensation coefficient is less than a valid value.

With regard to (1) it is advisable to choose the proportional gain of the voltage circuit close to the maximum allowable at the $T_{VS} \le 0.5\ T$: $K_{PU} = 1$. Fields of stability for $K_{pu} = 1$ according to (3) are shown in Fig. 3.

At that gain from the condition of the possible overcompensation at a temperature change in resistance of the motor circuit at 20 % ($k = 0.2$) from the expression (3) and graphs (fig. 3) can be determined that the integration time constant circuit must equal $T_{int} = (0.2\ ..\ 0.3)T_M$ at a time constant of the armature circuit $T_A = (0.1\ ..\ 0.4)T_M$. Choosing a time constant T_{int} more, it can increase the stability margin of the system. However, the system becomes more inertial. So the correct is setting for systems with not full compensation in one part of the temperature range, which reduces the overcompensation in the second part of the temperature range.

Better control in DCED with indirect speed measuring. The stability condition (1) for voltage control circuit limits the performance of speed control. Due to positive current FB when choosing the correct ratio of the current compensation gain K_{RU} this performance limit can be compensated. If it divide the positive FB in two components, one of the components shifting to the input of restriction circuit as shown by the dotted line in

Fig. 2, the remainder of the positive current FB will be responsible only for the current compensation, and transferred part will eliminate static error of the voltage control. For small deviations from the speed set value the positive and negative current FB on input of CC compensate each other, and ACS turns into astatic speed regulator. For the large signal error of control the current set value is limited by restriction circuit on the level I_{lim}. Moreover, due to the action of positive current FB the level of restrictions is reached earlier, and the output from limitations occurs later. Current varies with the maximum rate for a longer time, thereby improving performance of control. Upon entering to the active zone the transitional process occurs at relatively low values of the input signal. This reduces the overshoot (Fig. 4).

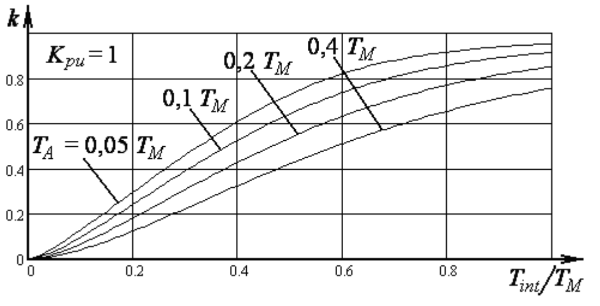


Fig. 3. Boundary values of the overcompensation coefficient of the static error of the speed control

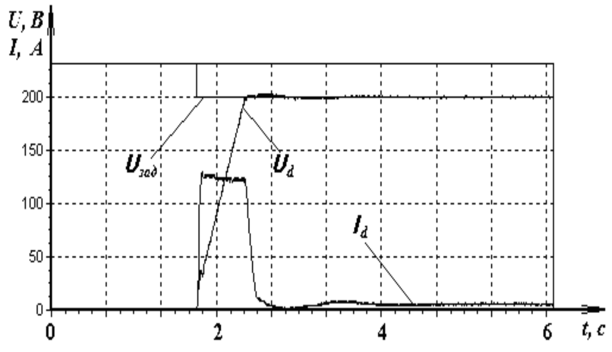


Fig. 4. Oscillogram of the transition process in DCED at a jump of the voltage set value

Stability fields of IM. Suppression of self-oscillation. Carried on the mathematical model calculations systematize as the stability fields in the coordinates: the scattering coefficient of the magnetic flux between stator and rotor σ and mechanical time constant τ_m relative to the stator time constant τ_1 $(\tau_m/\tau_1 = \tau'_m)$ at the ratio of the time constants of the rotor and stator $\tau_2 / \tau_1 = \tau'_2$ (Fig. 5) [2]. Calculations were performed for dependence between voltage and frequency with the normal magnetic flux of IM.

Given that the time constants are inversely proportional to resistances the curves (Fig. 5) show to such an extent of the field of instability increases with increasing resistance of the stator circuit, including the removal of IM from the frequency converter (FC) over long distances.

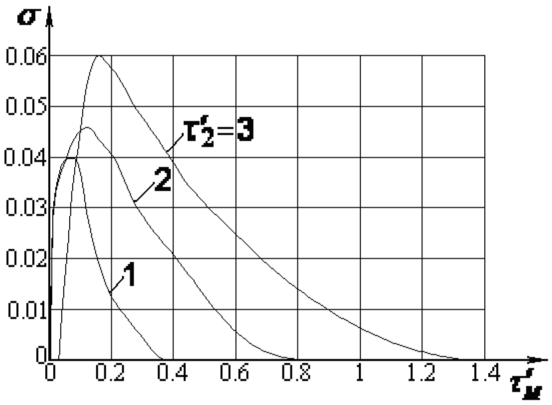


Fig. 5. Stability boundaries of IM

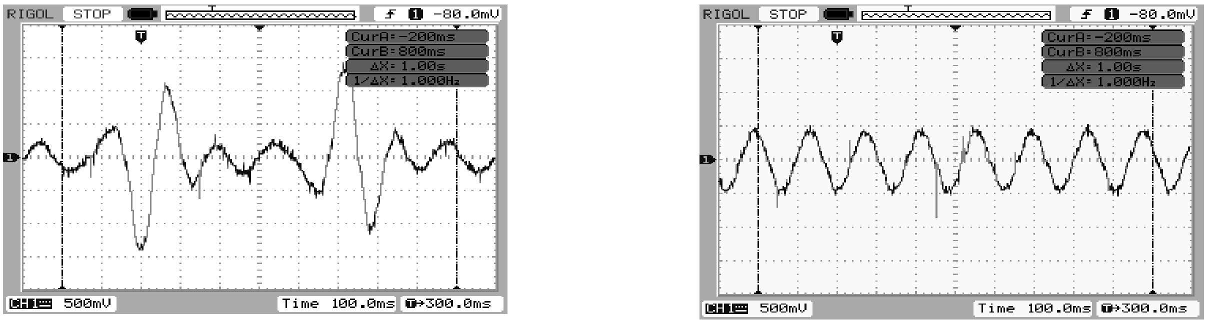
Fig. 6 shows photographs taken from the oscillograph screen, which displayed the phase current IM A02-81-4U3 in power 40 kW with a pulse-width modulation of the sinusoidal stator voltage with frequency f_{st} = 7 Hz and nominal magnetic flux in the system without FB (Fig. 6, *a*) and with FB on reactive current component in the FC (Fig. 6, *b*). Out of one cell in the vertical – 40 A, in the horizontal – 100 ms.

By simulation revealed that the oscillations on IM can be suppressed by the negative feedback of the active component of the current, so oscillations can not be shown at the AED having this FB. A preferred method to suppress the self-oscillation is the introduction of positive FB of reactive current component I_X (Fig. 6, *b*), using its variable component does not change the static control accuracy.

Speed control in AED. Structure of speed control system of AED at a constancy of the rotor magnetic flux is similar to that shown in Fig. 2 for DCED. This structure can be reduced to Fig. 7 for the variables in relative terms, where $\bar{I}_{RE}$, $\bar{I}_{RE.c}$ are the active component of drive current towards EMF of rotor and its steady-state value; T_1, T_{int} are current controller parameters, T_C is the equivalent time constant of the stator circuit. The parameters of controller for which the system at full compensation of slip (K = 1) has a sufficient margin of stability can be determined from formula (3) or from the graphs Fig. 3 with the corresponding renaming of parameters. The variable component of the positive FB of reactive current $\tilde{I}_{XE}$ suppresses the possible oscillations of IM and practically does not effect to the control process. The active component of the rotor current is determined according to measuring currents of two phases. Because of possible non-identical of sensors the error of determine current is greater than in the DCED, and calculated values can differ during the period of output frequency, thus periodically changing the values of the active current component occurs and the proportional part of the PI-controller can cause frequency instability even in steady-state mode of FC. Therefore, it is advisable to use an integral-controller (T_1 = 0), which turns into inertial link by FB and averages variation in the measuring of the active component of the rotor current. In this case the stability condition takes the form (4) with the difference that it should bear in mind the equivalent time constant of the stator circuit T_C instead of the time constant of armature circuit T_A.

This condition implies that it should choose integration time constant T_{int} which is comparable to the mechanical time constant of motor T_M to ensure sufficient stability margin.

The considered control system is implemented on the basis of microcontrollers KR196CA, dsPIC30F, dsPIC33F in electric drives of AC and DC produced by Zaporizhia Electrical Equipment Plant and Ukraine Science Research Institute of the Power Electronics.



a *b*

Fig. 6. Oscillograms the IM phase current with the sinusoidal pulse width modulation of the stator voltage, modulating frequency – 7 Hz at nominal magnetic flux: a – without FB; b – with FB on reactive current component

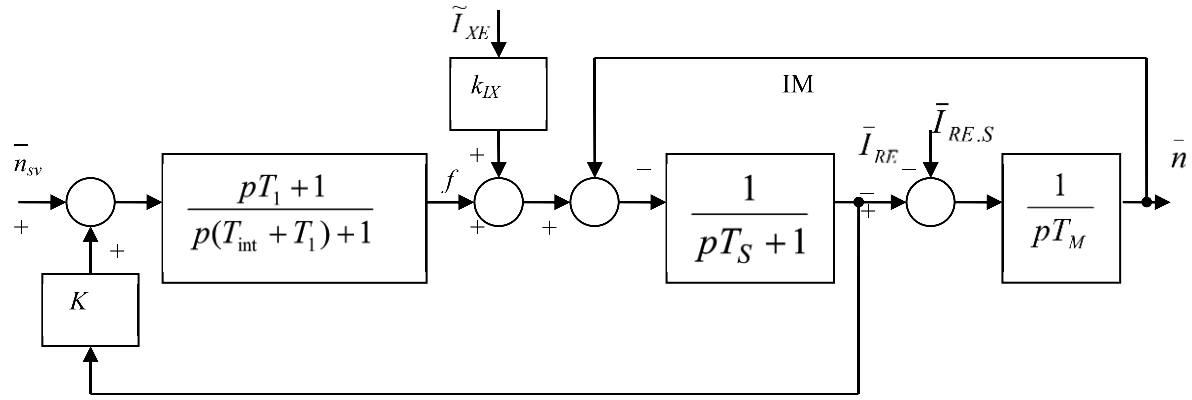


Fig. 7. Control structure of AED with the indirect speed measuring

Conclusions. Using the proposed control structure and methods of determining of the controller parameters gives the opportunity to improve the quality of control of electric drives with indirect speed measuring - to improve static accuracy of speed control and improve the dynamics by choice of parameters of controller with given stability margin.

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Мета. Узагальнення результатів проведених досліджень особливостей регулювання електроприводів з непрямим вимірюванням швидкості, пов'язаних із наявністю додатного зворотного зв'язку за струмом, значними пульсаціями сигналу зворотного зв'язку по напрузі в електроприводі постійного струму, проявом нестійкості асинхронного електродвигуна, і розгляд їх практичного використання для підвищення якості регулювання

Методи. Розглянуто методи підвищення якості регулювання за рахунок: повної компенсації статизма механічної характеристики електродвигуна при деякій середній температурі обмоток з допущенням перекомпенсації при зміні температури; зменшення інерційності датчика напруги при цифровому згладжуванні пульсацій мікропроцесорною системою управління в електроприводі постійного струму; забезпечення стійкості асинхронного двигуна в електроприводі змінного струму.

Результати. Визначені області стійкості системи регулювання при додатному зворотному зв'язку за струмом в електроприводі постійного струму та за активною складовою струму в асинхронному електроприводі. Визначені області стійкості контуру регулювання з тиристорним перетворювачем при цифровому згладжуванні пульсацій сигналу зворотного зв'язку. Визначені області стійкості асинхронного електродвигуна в залежності від коефіцієнта розсіювання магнітного потоку, електромеханічної постійної часу, постійних часу статора й ротора. Обґрунтовані структурні схеми та параметри системи, що забезпечують якісне регулювання електроприводу.

Наукова новизна. Методика вибору параметрів регулятора швидкості при додатному зворотному зв'язку за струмом. Межі стійкості контуру регулювання з тиристорним перетворювачем при цифровому згладжуванні пульсацій сигналу зворотного зв'язку. Межі стійкості асинхронного двигуна в залежності від коефіцієнта розсіювання магнітного потоку та постійних часу ротора, статора, електромеханічної. Удосконалення структурних схем системи регулювання електроприводів з непрямим вимірюванням швидкості .

Практична значимість. Впровадження результатів досліджень в електроприводах постійного й змінного струму, що випускаються ПАТ „Запорізький електроапаратний завод“, в електроприводах, випущених ВАТ НДІ „Перетворювач“.

Ключові слова: *електропривод, система регулювання, стійкість, тиристорний перетворювач, асинхронний електродвигун*

Цель. Обобщение результатов проведенных исследований особенностей регулирования электроприводов с косвенным измерением скорости, связанных с наличием положительной обратной связи по току, значительными пульсациями сигнала обратной связи по напряжению в электроприводе постоянного тока, проявлением неустойчивости асинхронного электродвигателя, и рассмотрение их практического использования для повышения качества регулирования.

Методы. Рассмотрены методы повышения качества регулирования за счет: полной компенсации статизма механической характеристики электродвигателя при некоторой средней температуре обмоток с допущением перекомпенсации при изменении температуры; уменьшения инерционности датчика напряжения при цифровом сглаживании пульсаций микропроцессорной системой управления в электроприводе постоянного тока; обеспечения устойчивости асинхронного двигателя в электроприводе переменного тока.

Результаты. Определены области устойчивости системы регулирования при положительной обратной связи по току в электроприводе постоянного тока и по активной составляющей тока в асинхронном электроприводе. Определены области устойчивости контура регулирования с тиристорным преобразователем при цифровом сглаживании пульсаций сигнала обратной связи. Определены области устойчивости асинхронного электродвигателя в зависимости от коэффициента рассеяния магнитного потока, электромеханической постоянной времени, постоянных времени статора и ротора. Обоснованы структурные схемы и параметры системы, которые обеспечивают качественное регулирование электропривода.

Научная новизна. Методика выбора параметров регулятора скорости при положительной обратной связи по току. Границы устойчивости контура регулирования с тиристорным преобразователем при цифровом сглаживании пульсаций сигнала обратной связи. Границы устойчивости асинхронного двигателя в зависимости от коэффициента рассеяния магнитного потока и постоянных времени ротора, статора, электромеханической. Совершенствование структурных схем системы регулирования электроприводов с косвенным измерением скорости.

Практическая значимость. Внедрение результатов исследований в электроприводах постоянного и переменного тока, выпускаемых ПАО „Запорожский электроаппаратный завод“, в электроприводах, выпущенных ОАО НИИ „Преобразователь“.

Ключевые слова: *электропривод, система регулирования, устойчивость, тиристорный преобразователь, асинхронный электродвигатель*

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