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# SYNTHESIS OF THE ELECTRICAL DRIVE CONTROL SYSTEM BY THE N–i SWITCHING METHOD WITH REFINED JERK PREDICTION

# СИНТЕЗ СИСТЕМИ КЕРУВАННЯ ЕЛЕКТРОПРИВОДОМ МЕТОДОМ N–i ПЕРЕМИКАНЬ ПРИ УТОЧНЕНОМУ ПРОГНОЗУВАННІ РИВКА

*The relevance of the work is due to the need to adapt the methods of the optimal control theory to the possibilities of their modern technical implementation. The purpose of the study is to improve the quality of transients of relay velocity control systems of an electric drives, synthesized by the N–i switching method. The detailing of the diagrams of the speed-optimized transient of the electric drive ensured an increase in the accuracy of jerk prediction. The use of the proposed method of determining coordinate constraints allows synthesizing a control system that adjusts the velocity according to the optimal trajectory. The prospect of practical application of the results of the work lies in their integration into adaptive algorithms for parametric synthesis of digital controllers.*

***Keywords**: sliding mode control system, N–i switching method, transient, optimality in speed.*

*Актуальність роботи зумовлена необхідністю адаптації методів теорії оптимального керування до сучасних технічних можливостей. Складність варіаційних методів призвела до створення альтернативних засобів оптимізації, до яких належить метод N–i перемикань. Він відрізняється граничною простотою, проте узагальнення математичного апарату на довільний порядок здійснюється на основі спрощувальних допущень, що знижує ефективність методу стосовно систем низького порядку.*

*Метою цього дослідження є удосконалення математичного апарату методу N–i перемикань за рахунок наближення налаштувань регуляторів до оптимальних на основі уточненого розрахунку прогнозованої траєкторії перехідного процесу.*

*Для досягнення поставленої мети у роботі розв'язано такі задачі: здійснено побудову фрагмента перехідної траєкторії з урахуванням дії внутрішніх зворотних зв'язків електромеханічної системи; для деталізації діаграми перехідного процесу, яка має форму криволінійної трапеції, використано прямокутну діаграму, еквівалентну за величиною першого інтеграла за* *часом; визначено середнє значення ривка на інтервалі сталості напруги силового перетворювача і на цій основі визначено модифіковане значення коефіцієнта зворотного зв'язку релейного регулятора швидкості; проведено порівняльне дослідження систем керування електроприводом з базовими та модифікованими налаштуваннями, що підтвердило ефективність запропонованого рішення.*

*Результатом роботи є доповнення до математичного апарату методу N–і перемикань, орієнтоване на оптимізацію систем другого порядку. Його реалізація не вимагає залучення великих додаткових ресурсів та забезпечує покращення якості перехідних процесів. Перспективним напрямом продовження цього дослідження є інтеграція запропонованої методики до адаптивних алгоритмів налаштування релейних систем оптимального керування.*

***Ключові слова**: релейна система керування, метод N–і перемикань, перехідний процес, оптимальність за швидкодією.*

## Problem's Formulation

One of the main requirements for modern electromechanical systems [1, 2] is optimality in terms of speed. It is achieved on the basis of the prediction of motion trajectories using any known methods [3, 4, 5], so it is extremely important to ensure the reliability of such prediction. From these considerations, subordinate control systems are a convenient object for optimization, since the stabilization of intermediate coordinates at known levels is a significant prerequisite for the reproducibility of the designed movement, which in turn makes it predictable with high accuracy [6]. But the jerk belongs to the values, the stabilization of which for most mechanisms is not applied due to the insignificant influence of the nature of its change on the transient processes as a whole. Such an approach to the structural implementation of precision systems requires special measures to refine the calculated values of the jerk in order to obtain the desired quality of real transients as a result of speed optimization.

## Analysis of recent research and publications

The use of transistor inverters in modern electric drives [1, 2] as power converters is a premise for the widespread use of relay controllers [7, 8], which are a typical structural solution for implementing algorithms for optimal control in terms of accuracy and speed [3, 4, 5]. Coordination of single switching in cascaded controllers [6] by binding to the characteristic points of the predicted optimal in speed transient trajectory is the main idea of the N–i switching method [9]. According to this method, at the stage of synthesis, an assumption is made about the constancy of the jerk at the intervals of constancy of the voltage of the converter [10—13]. It allows us to unify the fragments of the designed trajectory that correspond to such intervals, and is very productive in a theoretical sense [9]. In reality, this assumption is not fulfilled at any of the mentioned intervals [12, 13] due to the action of internal feedbacks of the electromechanical system, as a result of which the designed value of the jerk is only approximately equal to its real value. This causes a deviation of the movement of control systems of electric drives from the calculated trajectories [12—14]. In most cases, the short relative duration of voltage constancy intervals makes it possible to neglect such deviations without a significant effect on the performance of systems [9, 12, 13]. However, such systems cannot be considered strictly optimal in terms of speed.

## Formulation of the study purpose

The assumption about the constancy of the jerk reduces the efficiency of the N–i switching method [12, 13] in the synthesis of control systems for electric drives. In a number of works, measures have been proposed to compensate for deviations of the real trajectories of the synthesized systems from the designed ones, but their effect is partial [9, 12, 13]. Therefore, it is relevant to create a technique for refining the predicted value of the jerk, taking into account the shape of the transitional trajectory of the system [11], which significantly depends on the magnitude of the driving action.

## Presenting main material

The system of differential equations for the dynamics of a DC electric drive with a high-speed transistor converter [1, 6, 9] has the form

$$\left.\begin{aligned} p\omega &= \frac{c}{J}\cdot(i - i_c) \\ pi &= \frac{u - R\cdot i - c\cdot\omega}{L} \end{aligned}\right\}, \tag{1}$$

where $i$ — armature current, $i_c$ — static current, $u$ — voltage of the armature circuit, $\omega$ — angular velocity of the motor shaft, $L$, $R$ — inductance and active resistance of the armature circuit, $c = k\Phi$ — coefficient that is a constant at a constant magnetic flux, $J$ — moment of inertia of the electromechanical system, which is determined by the sum of the moments of inertia of the armature and the moments of inertia of the gearbox and the working body reduced to the motor shaft, $p = \frac{d}{dt}$ — symbol of differentiation in time.

According to the N–i switching method, in order to build an optimal control system for a dynamic object (1), it is necessary to apply [9, 13] a cascade of relay controllers

$$\left.\begin{aligned} u_{R\omega} &= \varepsilon^* = \varepsilon_{max}\cdot sign\left(\omega^* - \omega - K_{\omega\varepsilon}\cdot\varepsilon\right) \\ u_{R\varepsilon} &= u^* = u_{max}\cdot sign\left(\varepsilon^* - \varepsilon\right) \end{aligned}\right\}, \tag{2}$$

where $\omega, \varepsilon$ — angular velocity and acceleration of the motor shaft, the symbol "*" denotes the specified values of the corresponding variables, both input and generated by the regulators for the subordinate elements of the system; indexes "max" indicate the levels of constraint of state coordinates; $K_{\omega\varepsilon}$ — feedback factor of the velocity controller on acceleration, $u_{R\omega}, u_{R\varepsilon}$ — signals of the velocity and acceleration controllers.

Closing with flexible feedback [6, 15] the internal control loop of the cascade (2) makes not only static, but also dynamic properties of the control system independent of the action of the resistance torque. The acceleration stabilization loop provides the same rate of transients at an arbitrary value of the resistance torque, which does not go beyond the loading capacity of the electric drive [9].

Parametric synthesis of controllers (2) requires determining the levels of acceleration and jerk restrictions $\varepsilon_{max}, a_{max}$ by substituting the maximum values of current and voltage $i_{max}, u_{max}$ into the equations of unperturbed motion of the control object (1) at zero levels of its internal feedbacks

$$\left.\begin{aligned} p\omega &= \varepsilon = \frac{c}{J}\cdot i \\ p\varepsilon &= a = \frac{c}{J}\cdot\left(\frac{u - R\cdot i - c\cdot\omega}{L}\right) \end{aligned}\right\}, \tag{3}$$

which leads to the formulas

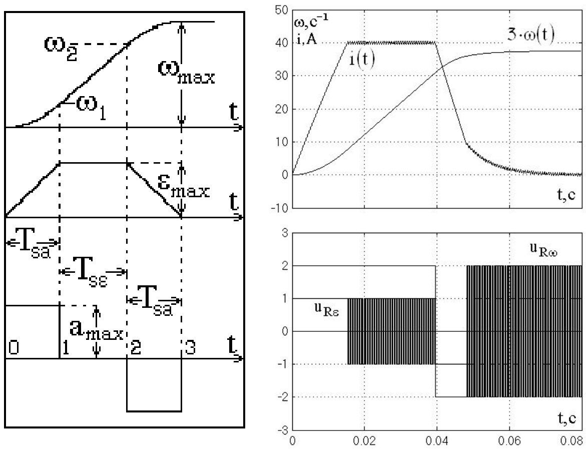
$$\varepsilon_{max} = \frac{c}{J}\cdot i_{max}, \tag{4}$$

$$a_{max} = \frac{c}{J}\cdot\frac{1}{L}\cdot u_{max}. \tag{5}$$

The designed trajectories [9] for the most general case of the speed-optimal acceleration process shown in Fig. 1 are easily predictable based on the limiting values of coordinates (3), (5). The task of synthesizing the parameters of relay systems of the second order by the N–i switching method [6, 9] is to provide a single switching of the controller $R_\omega$ at a characteristic point of the trajectory, which has the designation 2 in Fig. 1, *a*, or the designation 1 in Fig. 2, *a*. The result of its analytical solution [11, 13] is the expression for the feedback coefficient

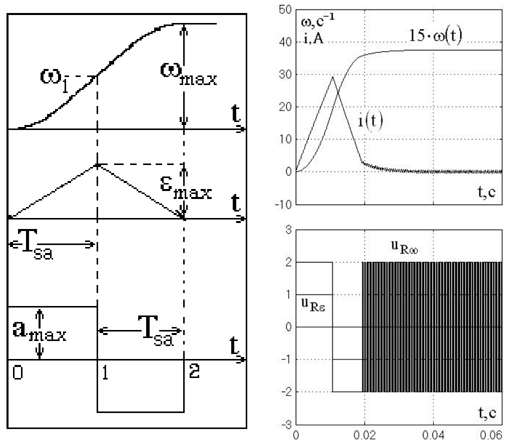
$$K_{\omega\varepsilon} = \frac{\varepsilon_{max}}{2\cdot a_{max}}. \tag{6}$$

If during acceleration to velocity $\omega_{max}$ with jerk constraint $a_{max}$, the maximum acceleration [9, 11] cannot be achieved, at which a triangular diagram $\varepsilon(t)$ is formed (Fig. 2, *a*)




*a* *b*

*Fig. 1.* Designed (*a*) and real (*b*) diagrams of transient with a trapezoidal acceleration profile




*a* *b*

*Fig. 2.* Designed (*a*) and real (*b*) diagrams of transient with a triangular acceleration profile

$$\varepsilon_{trg} = \sqrt{\omega_{max} \cdot a_{max}}\,, \tag{7}$$

this value must be set as the appropriate restriction level [9]

$$\varepsilon_{max} = \varepsilon_{trg}\,. \tag{8}$$

Let's turn to the control object (1) with the following parameters and intermediate coordinates restriction levels:

$$R = 1\Omega,\, c = 4V \cdot s,\, L = 0.1H,\, J = 0.5kg \cdot m^2, \omega_n = 50\,s^{-1},\, i_n = 20\,A, u_n = 220V. \tag{9}$$

The given data is obtained on the basis of the characteristics of the electric drive with a 4 kW DC motor by rounding the parameters and values. In addition, the inductance of the armature circuit is increased by about an order of magnitude. Such a correction is made for the convenience of transient analysis. Index "n" in (9) and below denotes rated values.

Let's set the current and voltage constraints on the levels

$$i_{max} = 2 \cdot i_n, u_{max} = 1.3 \cdot u_n\,. \tag{10}$$

Substituting the maximum values of the coordinates of the electromechanical system, determined according to (10), into formulas (4), (5), we obtain the constraints of acceleration and jerk

$$\varepsilon_{max} = 320\,s^{-2},\, a_{max} = 22880\,s^{-3}, \tag{11}$$

which determine the coefficient (6) of the velocity controller feedback on acceleration

$$K_{\omega\varepsilon} = 0.007\ s \tag{12}$$

when tuned for transient with a trapezoidal diagram $\varepsilon(t)$. Time diagrams of acceleration process of the electric drive to a set velocity $\omega^* = 0.25 \cdot \omega_n = 12.5\,s^{-1} = \omega_{max}$ are shown in Fig. 1, *b*. Note that the controller signals $u_{R\omega}, u_{R\varepsilon}$ are shown in relative units with scales that correspond to their role in the cascade hierarchy (2). Transient processes proceed with undershooting, which occurs due to the premature entry of the velocity controller into the sliding mode at time $t = 0.047\,s$. The prematureness of the sliding mode of controller $R_\omega$ is evidenced by the acquisition of an exponential shape by the curves $i(t), \omega(t)$ at $t > 0.047\,s$.

When setting up the system (1), (2) with the data (9), (10) to work out the specified velocity $\omega^* = 0.05 \cdot \omega_n = 2.5\,c^{-1} = \omega_{max}$ the following condition is not met

$$\varepsilon_{max} \le \varepsilon_{trg}\,, \tag{13}$$

therefore, the calculation of the parameters is carried out according to formulas (7), (8), (6) and gives the values

$$\varepsilon_{max} = 239\, s^{-2} \ , \ K_{\omega\varepsilon} = 0.0052\ s\,. \tag{14}$$

The transients of such a system, shown in Fig. 2, *b* also demonstrate the discrepancy between the real diagrams and the time-optimal ones at $t > 0.019\,s$.

The time diagrams of transients obtained in the given examples have a form that is typical for electric drive control systems synthesized by the N–i switching method [9, 11—13]. But the reason lies not in the synthesis method as such, but in the applied method for determining the calculated jerk, when formula (5) is justified by the extension of transition diagrams (Fig. 1, *a*) of a system with a neutrally stable object to electromechanical systems with an arbitrary structure. Therefore, for electric drives (1), (2), in addition to violation of the assumption

$$u(t) = const \ \Rightarrow \ a(t) = const\,, \tag{15}$$

on any interval of constancy $u(t)$ the following equality also fails

$$|a(t)| = a_{max} \tag{16}$$

due to the action of internal feedbacks of the control object.

Due to such a discrepancy between the predicted diagram $a(t)$ and its real form, both the velocity and acceleration increments in the time intervals between single switching of the relay controllers turn out to be different from the calculated ones. But the optimal parameter (6) of the controller $R_\omega$ is determined [9] precisely by the ratio of these increments. Therefore, the motion of systems synthesized with non-observance of conditions (15), (16) is somewhat different from the expected one.

Despite the impossibility of fulfilling condition (15) by structure (1), (2), it is possible to approach the fulfillment of assumption (16) in the mathematical apparatus of the N–i switching method. The solution to this problem lies, firstly, in averaging the calculated values of the jerk obtained at the boundaries of the interval of constant voltage $t_m$ — $t_n$ (Fig. 3), and, secondly, in taking into account the formula for calculating the jerk of all members of the second equation of the system (3). As a result, instead of formula (5), it is possible to compose the following expression

$$a_{max} = \left|\frac{a_{max}(t_m) + a_{max}(t_n)}{2}\right| = \frac{1}{2}\cdot\frac{c}{J}\cdot\frac{1}{L}\cdot\left|u(t_m) - R\cdot i(t_m) - c\cdot\omega(t_m) + u(t_n) - R\cdot i(t_n) - c\cdot\omega(t_n)\right|. \tag{17}$$

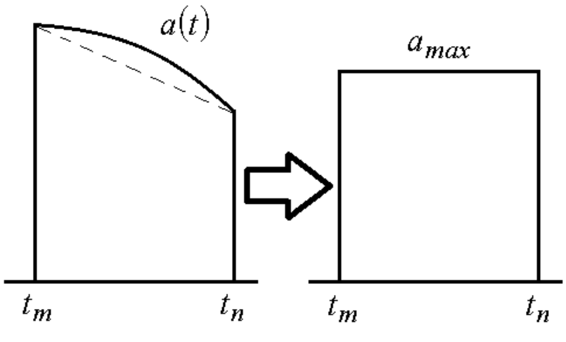



*Fig. 3.* Approximation of the real time diagram of the jerk by a piecewise constant function

Finding $a_{max}$ according to expression (17) implies the replacement of diagrams, equivalent in value to the integral of $a(t)$ on the time interval of voltage constancy, i.e. ensures the equality of the areas of the curvilinear trapezoid and the rectangle under the real and calculated jerk diagrams (Fig. 3). This replacement does not give an exact averaging of the jerk, since formula (17) provides for a linear interpolation of the curvilinear side of the trapezoid (dotted line in Fig. 3), but significantly reduces the error in predicting the value of $a_{max}$.

Correlating time points 2, 3 (Fig. 1, *a*) with moments $t_m$, $t_n$ (Fig. 3), we find the values of the coordinates on the designed diagrams for substitution into formula (17) in order to determine $a_{max}$ more precisely:

$$\begin{aligned} &u(t_m) = -u_{max}, i(t_m) = i_{max}, \omega(t_m) = \omega_2 = \omega_{max} - \omega_1, \\ &u(t_n) = -u_{max}, i(t_n) = 0, \omega(t_n) = \omega_{max}. \end{aligned} \tag{18}$$

Value

$$\omega_1 = \frac{1}{2}\frac{\varepsilon_{max}^2}{a_{max}} \tag{19}$$

in (18) has the meaning of an increase in velocity [9] in the intervals of change in acceleration (Fig. 1, *a*, Fig. 2, *a*). To find $a_{max}$ using formula (18), you need to know $\omega_1$ depending on $a_{max}$ according to (19). This logical circle can be broken by using for the calculation $\omega_1$ the previously found according to (6) value $a_{max}$, which we denote by $a_{max0}$:

$$a_{max0} = \frac{c}{J}\cdot\frac{1}{L}\cdot u_{max}\,. \tag{20}$$

The reason for this is the approximate nature of both formulas (5), (17), where formula (5) is the first approximation of formula (17). Therefore, use the calculation expression

$$\omega_1 = \frac{1}{2}\frac{\varepsilon_{max}^2}{a_{max0}}\,. \tag{21}$$

By substituting formulas (20) into (21) and (18) into (17), we obtain a refined expression for determining the estimated jerk $a_{max}$

$$a_{max} = \frac{1}{2}\cdot\frac{c}{J}\cdot\frac{1}{L}\cdot\left(2u_{max} + R\cdot i_{max} + c\left(2\omega_{max} - \omega_1\right)\right). \tag{22}$$

For acceleration modes with a triangular acceleration diagram (Fig. 2, *a*), instead of formulas (20), (21), the calculation expression should be used

$$\omega_1 = \frac{1}{2}\omega_{max}\,. \tag{23}$$

In addition, the development of a triangular acceleration diagram leads to a decrease in the maximum current in formula (22) relative to its initial limitation level to the level $i_{max\,trg}$. This change is proportional to the decrease in the maximum acceleration from the level $\frac{c}{J}i_{max}$ defined by formula (4) to the actual one $\varepsilon_{max}$ and gives the following maximum current value:

$$i_{max\,trg} = i_{max}\cdot\frac{\varepsilon_{max}}{\frac{c}{J}i_{max}} = \frac{J\cdot\varepsilon_{max}}{c}\,. \tag{24}$$

Let's synthesize the control system (1), (2) with parameters (9), (10) according to the refined method for the cases of tuning to the specified velocity considered above (Fig. 1, *b*, Fig. 2, *b*)

1) $\omega^* = 0.25\cdot\omega_n = 12{,}5s^{-1} = \omega_{max}$,  2) $\omega^* = 0.05\cdot\omega_n = 2{,}5s^{-1} = \omega_{max}$,

which correspond to trapezoidal and triangular acceleration or current diagrams. In the first case, the sequence of formulas (4), (5), (20), (21), (22), (6) is used, which instead of the values (11), (12) gives the updated system settings

$$\varepsilon_{max} = 320\,s^{-2},\; a_{max} = 28189\,s^{-3}, \tag{25}$$

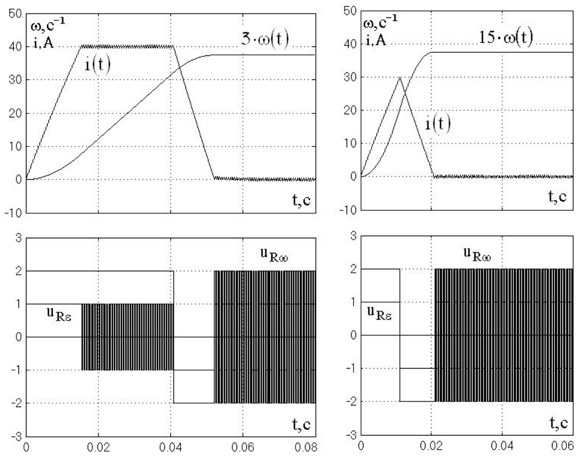
$$K_{\omega\varepsilon} = 0.0057\ s\,. \tag{26}$$

In the second case, the sequence of formulas (4), (5), (20), (23), (24), (22), (6) is used, which instead of the values (14) gives the results

$$\varepsilon_{max} = 239\,s^{-2},\; a_{max} = 24676\,s^{-3}, \tag{27}$$

$$K_{\omega\varepsilon} = 0.0048\ c\,, \tag{28}$$

where $a_{max}$ is also modified in contrast to the settings obtained by the basic version of the N–i switching method. It should be emphasized that different values of $a_{max}$ in data sets (11), (25), (27) refer to the calculated levels of jerk constraint for the synthesis of controllers based on different fragments of transients, which correspond to intervals of constant voltage with the same real amplitude $u_{max}$.




*a* *b*

*Fig. 4.* Transients of modified electric drive control systems with trapezoidal (*a*) and triangular (*b*) acceleration profiles

The results of simulating the dynamics of the control system of the electric drive for these two cases, shown in Fig. 4, demonstrate the complete correspondence of the form of the obtained transients to the designed time diagrams (Fig. 1, *a*), (Fig. 2, *a*). The absence of undershoots or overshoots indicates the achievement of optimality in terms of speed for given coordinate constraints. The achieved quality of transients allows us to assert that expression (22) together with formulas (19), (23), (24) provides a high degree of approximation of the predicted value of $a_{max}$ to the real constraint of jerk for both types of the acceleration diagram.

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## Conclusions

The result of the presented study directly solves the problem inherent in the N–i switching method due to the adoption of simplifying assumptions necessary for its generalization to an arbitrary order of the system. The implementation of this result provides a significant reduction in the duration of the transients, eliminating the need to use means of additional correction of parameters [13]. But the described procedure for refined prediction of jerks, based on detailing the designed section of the optimal trajectory of the electric drive control system, can be used not only as part of the mathematical apparatus of the N–i switching method. It can also be used with any drive control system speed optimization problem. The developed supplement to the synthesis method is focused on integration into the algorithms [10, 11] of setting digital control systems, which is the prospect of its practical implementation.

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