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Control of Direct Current Electrical Machine: Stabilisation of Current and Speed by the Change of Voltage in the Armature for Direct Current in Excitation Winding

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Abstract: In the paper, we study the design basics of subordinate control system of direct current electric drive by the voltage change in armature with direct current in excitation winding. For the electrical transducer, we can use an electromechanical amplifier, a magnetic amplifier with rectifier that permit the regulation of output voltage through action on input signal.

Keywords: Stabilization; Armature voltage; Direct current; Electrical machine

I. INTRODUCTION

The electric circuit of electric drive with control on armature voltage is shown on Figure 1. The excitation winding LM is supplied from the current source $u_1 = u_N$, and the armature of electromotor M from the electrical transducer.

In the control system, we have the stabilization of armature current (electromagnetic moment), the speed and the position of functioning machine executive organ. The control information comes from current captors (CC) with Shunt (RS), Speed (BR) and Position (PC). The control system structure is built according to the principle of subordination control and is composed of current, speed and position loops [1].

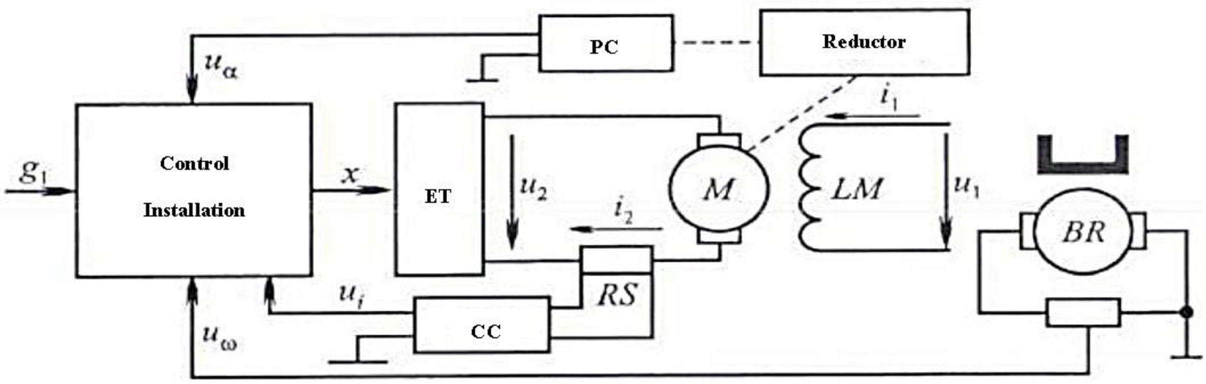

Figure 1: Electric circuit of direct current electric drive.

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II. DESIGN OF CURRENT LOOP REGULATOR FOR THE ELECTROMOTORARMATURE

The formation of given dynamic characteristics of armature current will be done by the method of series correction. We form a control loop with regulator whose transfer function is W_{CR} (Figure 2) [2,3].

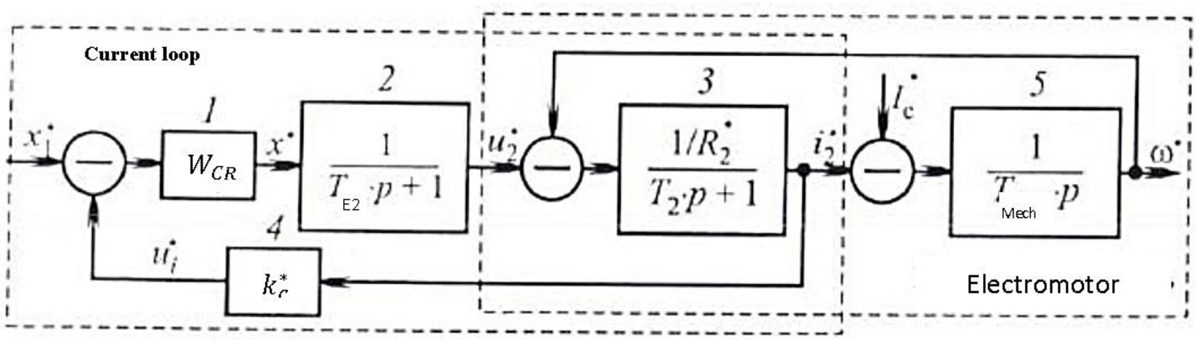

Figure 2: Control loop structural circuit: 1-Current regulator; 2-Electric transducer; 3-Electrical part of electromotor; 4-Current captor; 5-Mechanical part of electromotor.

The current loop must assure the stabilization of current (moment) on a level, given by input signal x_1^*.

2.1. Proportional-Integral Current Regulator

Let us define a simplified method for determination of transfer function of armature current regulator. We assume that the mechanical time constant is sufficiently high and is greater than the time constant of armature current and electric transducer. That is why a variation of speed ω does not influence the dynamics of armature current.

That assumption gives the possibility not to consider the internal feedback of electromotor on speed and we can consider that elements 2 and 3 of the structural circuit in Figure 2 are linked in series and form the control object of current loop. Thus the current control loop object has the following transfer function:

$$w_{oc2} = \frac{1}{T_{E2}P+1} * \frac{1/R_2^*}{T_2P+1}$$

The choice of transfer function of series correction element current regulator w_{CR} will be executed such that assuring standard dynamic characteristics that will create hopeful transfer function, equation (1):

$$w_h = \frac{1/\mathrm{K}_C^*}{2*T_\mu^2*P^2+2*T_\mu p+1} \quad (1)$$

The transfer function of current regulator (2):

$$w_{CR} = \frac{1/\mathrm{K}_C^*}{w_{oc2}*2T_\mu*P*\left(T_\mu p+1\right)} = K_{r_2} + \frac{1}{T_{r_2}*P} \quad (2)$$

$$T_\mu = T_{E2};\ K_{r2} = R_2 * T_2 / \left(2K_c^* * T_\mu\right) \text{ and } T_{r2} = 2*Kc^* * T_\mu / R_2$$

The current loop with current regulator whose transfer function is defined by equation (2) will create transient process a little bit different from the etalon.

Let us consider the static control error provoked by neglecting the internal feedback of electromotor on speed. By using the structural circuit of control current loop (Figure 2) we have $x^* = \left(x_1^* - K_C^*.i_2^*\right).W_{CR}$

The equation for the armature current will be : $i_2^* = W_y.x_1^* + W_B.I_C^*$ (3)

Where $W_y = \dfrac{T_2P+1}{K_C^*} / Y(P)$ is the current loop transfer function on control signal X_1^*;

$W_B = 2.\varepsilon.\left(T_\mu P+1\right)/Y(P)$ Is the current loop transfer function on perturbation signal I_c^*;

$$\varepsilon = T_\mu / T_M \ ; \ \varepsilon = T_\mu / T_M = R_2^*.T_{Mech}$$

The characteristic polynom of transfer functions is $Y(P) = \left(T_2P+1\right).\left(2T_\mu^2P^2 + T_\mu P + 1\right) + 2.\varepsilon\left(T_\mu P+1\right)$

If we assume that P = 0 in eqaution (3), we have:

$$i_2^* = \frac{x_1^*}{K_C^*.\left(1+2\varepsilon\right)} + \frac{2\varepsilon.i_C^*}{\left(1+2.\varepsilon\right)}$$

From that equation, the static error on control signal is:

$$\Delta i_2^* = \frac{x_1^*}{K_C^*} - x_1^* / K_C^*.\left(1+2.\varepsilon\right) = \frac{x_1^*.2.\varepsilon}{K_C^*}.\left(1+2\varepsilon\right)$$

From the errors expressions, we see that their value is determined $\varepsilon = T_\mu / \mathrm{T_M}$

2.2. Proportional Intergral – Integral Current Regulator

For high value of $\mathcal{E}=T_\mu/T_M$ errors of loop current can be significant. We can obtain astatic control system with current if we consider internal feedback of electromotor on speed. In that case, the current control loop object is the transfer function.

$$i_2^* = W_{11}.x_1^* + W_{11}.i_C^*$$

The equation for the current regulator's transfer function is:

$$w_{CR} = \frac{1/\mathrm{K}_C^*}{w_{11}.2.T_\mu P\left(T_\mu p+1\right)} = K_{r_2} + \frac{1}{T_{r2}P} + \frac{1}{T_{r2}.T_M.P^2} \quad (4)$$

Where $T_\mu = T_{E2}$; $K_{r2} = \dfrac{R_2^*.T}{2.K_c^*.T_\mu}$; $T_{r2} = \dfrac{2.\mathrm{K}_2^*.T_\mu}{R_2^*}$; $T_M = R_2^*.T_{Mech}$

Thus, current regulator is composed of three components: proportional part, integral regulator of first order and integral regulator of second order.

The transfer functions of current loop on control X_1^* and perturbation I_c^* signals are defined as follows, equation (5):

$$W_y = \frac{i_2^*}{x_1^*} = \frac{1/K_c^*}{2.\mathrm{T}_\mu^2.P^2 + 2.T_\mu P + 1} \quad (5)$$

$$W_B = \frac{i_2^*}{I_C^*} = \frac{2\left(T_\mu p+1\right).T_\mu P}{\left(2.T_\mu^2.P^2+2.T_\mu P+1\right)+T_M.T_2 P^2+T_M P+1}$$

In those expressions, if we assume P=0 in the established regime armature current $i_{2M}^* = \frac{x_1^*}{K_c^*}$ is proportional to the control signal I_c^* and does not depend on resistance current I_c^*.

2.3. Two-Loop Current Regulator

To obtain an astatic control system with current is possible by building a second loop of current, whose control object is the first loop. The transfer function of first current loop W_y can be approximated by first order element:

$$w_y = i_2^* / x_1^* \approx \frac{1}{K_C^*} / \left(2T\mu P+1\right)$$

Then the second loop regulator on technical optimum will be integral:

$$w_{CR2} = \frac{1/K_c^*}{w_y * 2T\mu_1 P * \left(T\mu_1 P+1\right)} = \frac{1}{4T_\mu P}, \quad where T\mu_1 = 2T\mu$$

The structural circuit for two-loop control system of armature current is shown on Figure 3.

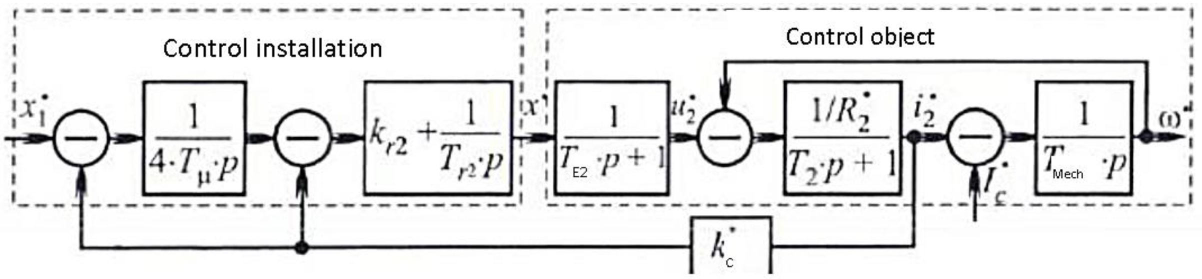

Figure 3: Two-loop control system of armature current.

III. LIMITATION OF ELECTROMOTOR ARMATURE CURRENT

The maximal value of armature current I_{max} should be limited from the views of assuring given static and dynamic loads of the electric drive mechanism and reliable functioning of collector mechanism [4].

The limitation of current at a given level $I_{\max}^*$ can be done by limitation of input signal of current loop x_1^*.

If the maximal value $I_{\max}^*$ is known, then the value $x_{1\max}^*$ is found through the expression of regulation characteristic $x_{1\max}^* = K_C^* \; I_{\max}^*$

We consider $x_{1\max}^*$ = 1, therefore the transfer coefficient of current captor in per – units $K_C^* = \frac{1}{I_{\max}^*}$.

The element of armature current limitation is non-linear. The relation between input signal x_2^* and output signal x_1^* can be described in the eqaution (6):

$$x_1^* = x_2^* \; for \; |x_2^*|<1 \text{ and } 1 \text{ for } |x_2^*| \geq 1 \quad (6)$$

The limitation of armature current element is established at the entrance of current loop, as shown in Figure 4.

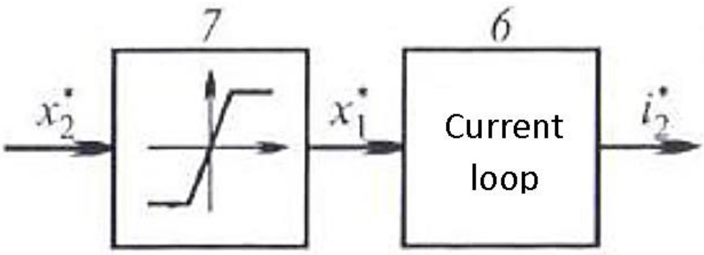

Figure 4: Current loop 6 and current limitation element 7.

IV. DESIGN OF REGULATOR FOR ARMATURE ROTATION SPEED OF ELECTROMOTOR

For regulation of armature rotation speed, we build speed control loop (Figure 5) [5]. This loop is assured by a convenient choice of speed regulator transfer function W_{Sr} . The transfer coefficient of speed captor is chosen in such a way that the maximal speed corresponds with basic control system signal U_B. In that case $K_S^* = \frac{1}{\omega_{\max}^*}$

For the choice of transfer function of speed regulator 8 we assume that the current limitator 7 functions on the linear part of characteristic "Input – Output" and the signal $x_1^* = x_2^*$. Theregulation object of speed loop is the mechanical part of electromotor 5 and current loop 6 (Figure 5)

The transfer function of current loop is defined by the choice of current regulator and it has etalon aspect (1) at mechanical part of electromotor:

$$W_{so} = \frac{1/K_c^*}{\left(2T_\mu^2 P^2 + 2T_\mu + 1\right).T_{Mech}P} \approx \frac{1/K_c^*}{\left(2T_\mu P + 1\right).T_{Mech}P}$$

The transfer function of speed regulator is chosen such that it has standard transfer function of speed loop aspect, equation (7):

$$W_h = \frac{1/K_c^*}{2T_\mu^2 P^2 + 2T_\mu P + 1} \quad (7)$$

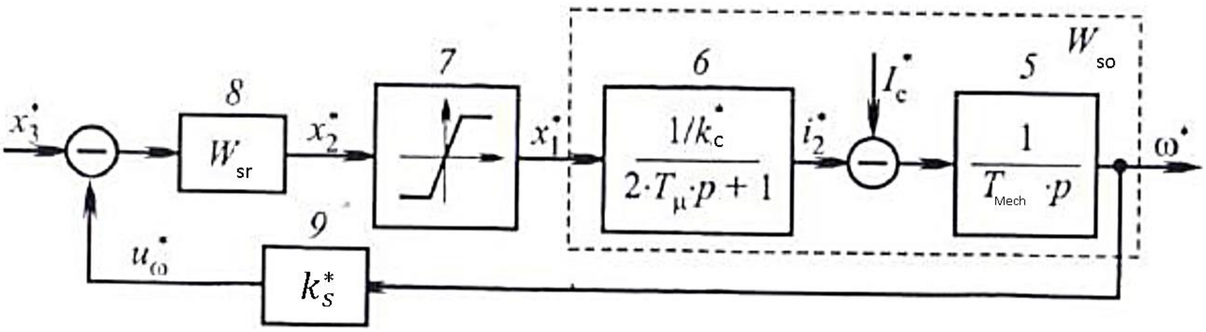

Figure 5: Structural circuit of armature rotation speed loop. 5- mechanical part of electromotor. 6 - current loop; 7- current limitator; 8- speed regulator; 9- speed captor.

If we assume Tμ1 = 2Tμ, then speed regulator transfer function will be a proportional element in equation (8):

$$W_{sr} = \frac{1/K_c^*}{W_{so}.2.T_{\mu 1}.P\left(T_{\mu 1}P + 1\right)} = \frac{K_c^* T_{Mech}}{K_S^*.4.T_\mu} = K_{sr}^* \quad (8)$$

Using the structural circuit of speed loop:

$$[x_3^* - k_s^*.\omega^*].\mathrm{W}_{sr}.\mathrm{W}_{so} - I_c^* = T_{Mech}.\mathrm{P}.\omega^*\text{, Or } \omega^* = W_{slc}.x_3^* - W_{slp}.I_c^* \quad (9)$$

Where $W_{slc} = \dfrac{1/K_S^*}{8T_\mu^3 P^3 + 8T_\mu^2 P^2 + 4T_\mu P + 1}$

;

$$W_{slp} = \frac{(2T_\mu^2 P^2 + 2T_\mu P + 1).4.T_\mu / T_{Mech}}{8T_\mu^3 P^3 + 8T_\mu^2 P^2 + 4T_\mu P + 1}$$

The transfer functions of speed loop on control and perturbation signal respectively.

If we assume on equation (9) P=0, then we have static electromechanical characteristic of electric drive with proportional speed regulator, equation (10):

$$\omega^* = x_3^* / K_s^* - (4.T_\mu / T_{Mech}).I_c^* \quad (10)$$

For I_c^* = 0, we have static characteristic of electric drive with proportional speed regulator, equation (11):

$$\omega^* = x_3^* / K_s^* \quad (11)$$

The static error for I_c^* = 1 is $\Delta\omega^* = -(4.T_\mu / T_{Mech})$ In open loop, static error for nominal load $\Delta\omega_0^* = -R_2^*$.

From the expressions of static errors for closed and open loop systems, it appears that in closed loop system, the static error $\Delta\omega^*$ decreases for $4.T_\mu / T_M$ times, when $T_M = R_2^* T_{Mech}$ is the electromechanical time constant.

V. DESIGN OF ADAPTIVE SPEED REGULATOR

The proportional speed regulator gives static error. If the level of error $\Delta\omega^* = -4T_\mu / T_{Mech}$ does not satisfy the technological process conditions, then we need to use an integral speed regulator. We therefore build a second speed loop [6].

The structural circuit of second speed loop is shown on Figure 6.

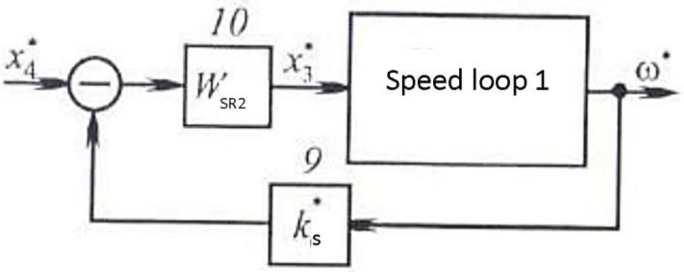

Figure 6: Structural circuit of second speed loop: 9-speed captor; 10- second speed loop regulator the first speed loop that has the transfer function.

$W_{slc} \approx \dfrac{1/K_s^*}{4T_\mu P+1}$ is the control object of the second speed loop. If the hopeful transfer function for second speed loop is $W_h = \dfrac{1/K_s^*}{2T_\mu^2 P^2 + 2T_{\mu_2} P+1}$

Then the transfer function of second speed regulator is:

$$WSr2{=}W_{sr2} = \frac{1/K_s^*}{W_{slc} * 2T_\mu P^* \left(T_{\mu_2} P+1\right)} = \frac{1}{8T_\mu P} \quad (12)$$

An integral element with $T_{\mu 2}{=}4T_\mu$

From Figure 6 we have $x_3^* = (x_4^* - k_5^* . \omega^*) * W_{sr2}$

By replacing that expression in (9), we find the Laplace representation of armature rotation speed, equation 9:

$$\omega^* = W_{slc2} * x_4^* - W_{slp2} * I_c^* \quad (13)$$

Where W_{slc2}, W_{slp2} transfer functions of speed loop $\omega*$ on control signal x_4^* and on perturbation signal I_c^* respectively.

We have;

$$W_{slc} = \frac{1/K_s^*}{\left(8T_\mu^2 P^2 + 4T_\mu P+1\right)^2};$$

$$W_{slp2} = 32\frac{\left(2T_\mu^2 P^2 + 2T_\mu P+1\right) * T_\mu^2 * P}{\left(8T_\mu^2 P^2 + 4T_\mu P+1\right)^2 * T_{Mech}}$$

If we assume in equation (13) that P=0, we have the expression for electromechanical characteristic of electric drive with proportional speed regulator $\omega^* = x_4^* / \mathrm{K}_S^*$. The static error is therefore equal to zero.
The dynamic error of speed stabilization is characterized by transient characteristic (Figure 7), created by the transfer function $W_{slp2} * T_{Mech} / T_\mu$.

The maximal speed drop for nominal load $\Delta\omega^* {=} {-}3{,}82\ T_\mu^* / T_{Mech}$ is reached for $t{=}5{,}9 T_\mu^*$

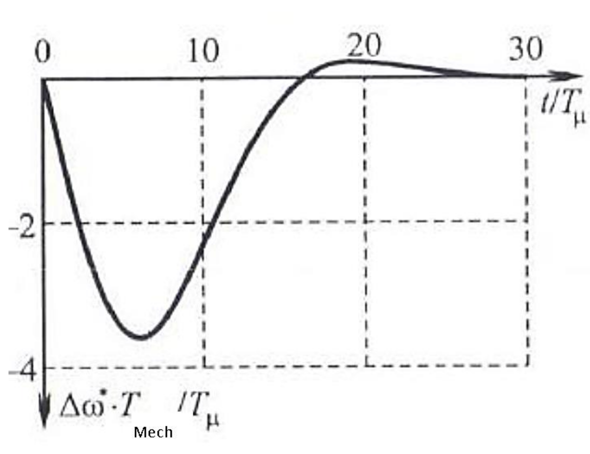

Figure 7: Transient characteristic created by transfer function $W_{slp2} * T_{Mech} / T_\mu$.

We can distinguish two functioning regimes of electric drive: current stabilization regime and speed stabilization regime. Obviously, in current stabilization regime, the integral speed regulator does not influence the armature rotation speed of electromotor. That is why its output expression in current stabilization regime will have various values and this will provoke oscillations on speed when crossing from current stabilization regime to speed stabilization regime.

To avoid such processes, the speed regulator in current stabilization regime should be a proportional element. In speed stabilization regime, the regulator should form two speed control loops with proportional and integral regulators.

Thus, the speed regulator should have different structures for current stabilization and for speed stabilization regimes. The regulator whose structure depends on electric drive functioning regime is called “adaptive”. An example of such structural circuit is shown on Figure 8.

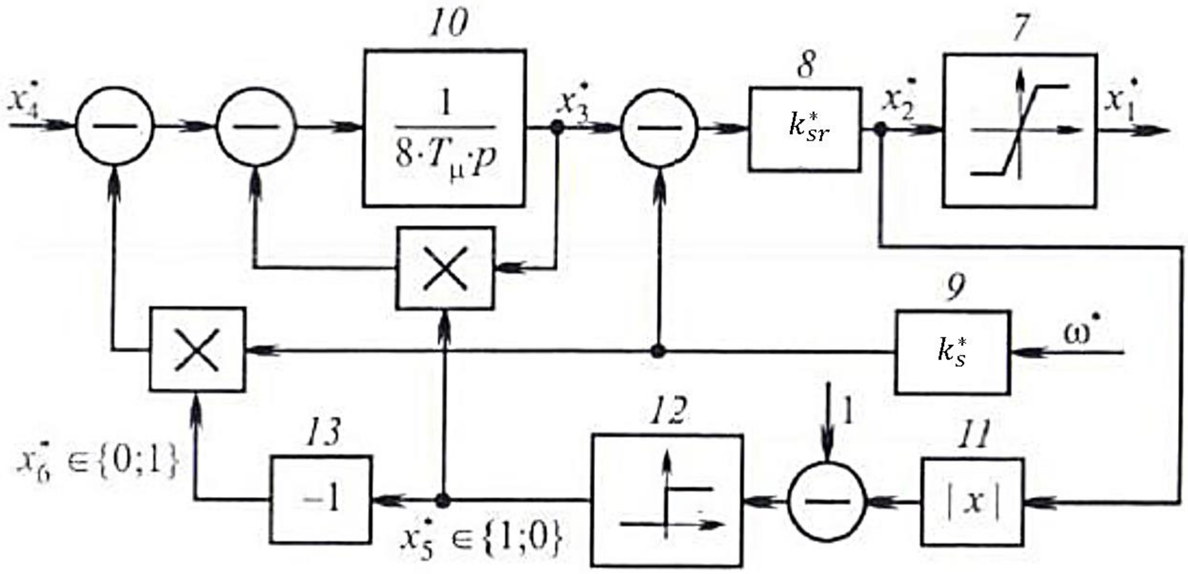

Figure 8: Structural circuit of adaptive speed regulator. 7- current limitator; 8- proportional speed regulator; 9- speed captor; 10- integral speed regulator; 11- element realizing the function of input signal module; 12- element realizing unit function; 13- element realizing logic inversion.

For the identification of electric drive functioning regime, we use the signal x_5^*=1(|x_2^*|−1), that has the value {1;0} with 1(x) – unit function. If x_5^*=1, then we have current stabilization regime and if x_5^*=0, then we have speed stabilization regime.

In current stabilization regime, x_5^*=1 and x_6^*=0.

In that case, the integral element 10 will have the following transfer function: $1/8T_\mu P+1$, and the feedback on speed ω^* is disconnected.

In speed stabilization regime, x_5^*=0 and x_5^*=1.

In that case, the integral element 10 is not surrended with feedback and the feedback on speed ω^* is connected. Thus, the second speed loop with adaptive regulator can stabilize the armature rotation speed of electromotor with sufficiently low dynamics and zero static error.

VI. CONCLUSION

For the formation of etalon dynamic processes in armature winding of direct current electrical machine with independent excitation, we use current control loop with integral- proportional regulator. This current control loop permits the stabilization of current in a given level.

For obtention of astatic current stabilization system, we need a regulator whose integral stabilisator is a second order one. For the armature current limitation in the input of control current loop, we need to install an element of input signal limitation.

For formation of etalon dynamic processes with control of armature rotation speed of direct current electrical machine with independent excitation, we need to build control loop with proportional regulator.

Speed stabilization static error depends on load current. In closed loop system with proportional regulator for nominal load, the static error decreases by $4T_{\mu} / T_M$ times compared to open loop system. For the obtention of astatic system of speed stabilization, we need an adaptive speed regulator

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