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Tuning of Control Loops of Electric Drives in Mechatronic Systems

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Abstract. The aim of the research is to assist the analysis and synthesis of controllers in the Electric Drives (ED) in mechatronic systems by studying current, speed and positional loops in adjustable electric drives. An approach for the synthesis of current, speed, and positional optimal regulators is presented. Based on the differential equations of the objects and their functional relations with the regulators, dynamic simulation procedures of given quality are obtained. Generalized structures of the considered EDs are derived and parameterized. The validity of the obtained results is confirmed by simulation verification procedures. The modeling is carried out by the MATLAB Simulink software. The approach is applicable to the synthesis of ED for mechatronic systems with DC and AC motors.

1. Introduction

Feedback is a central feature of life. The process of feedback governs how we grow, respond to stress and challenge, and regulate factors such as body temperature, blood pressure, and cholesterol level. The mechanisms operate at every level, from the interaction of proteins in cells to the interaction of organisms in complex ecologies. Multi-loop feedback systems with cascaded control are widely used in both DC and AC electric drives. In accordance with the principle of cascaded control of each of the controled object with a large time constant, a controller with a reverse transfer function in the structure of the control system must correspond. Insofar as there are inertial units in the structure of the control object, the controller must contain the appropriate number of forcing units. The complexity of the control object in the control loop uniquely determines the complexity of its controller. Based on a survey of over eleven thousand controllers in the refining, chemicals and pulp and paper industries, 97% of regulatory controllers utilize a proportional-integral-differential (PID) feedback control algorithm. If we limit ourselves to the PID - controller as the most complex of the linear ones, we would be left with the question of optimization of two types of loops with control objects, containing a first order transfer function (FOTF) unit with a small time constant (T_{mu}) and connected to it:

- FOTF unit with large time constant T_1>T_{mu};
- Integrator transfer function (ITF) unit with large time constant T_2> T_{mu}; T_2=1/ki.

When tuning a loop, the type and parameters of the controller are selected in such a way that the controller compensates the large time constants of the object and brings the transfer function of the loop to a normalized form taking into account the value of the small time constant (T_{mu}) and the selected optimization criterion. In practice, when adjusting the electric drive systems, two criteria for optimal adjustment of the control loops are mainly used: technical (modular) optimum (TO/MO) and

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symmetrical optimum (SO). First proposed by C. Kessler in the 1950s [4], [5] and widely used in DC electric drives, these criteria have not lost their relevance today.

Simple and convenient for practical use, these methods provide quality indicators that in most cases meet the set requirements. These classical methods strongly capture the attention of specialists in the field of control systems, engaged in the design and creation of quality electric drives, with the development of new methods for identification of technological processes, and adjustment of industrial controllers [6]. Despite the numerous publications dedicated to the practical optimization of control systems, several issues concerning the choice of optimization criteria, the quality of interference handling, the methods for setting up systems with sequential correction, etc., remain unresolved. The new areas of practical use require further development taking into account the growing requirements for the quality of control and the capabilities of the modern element base [1], [2], [3].

The aim of the research is to develop generalized standard methods for optimization of the circuits in the control systems of the electric drives, systematization and supplementation of the quality indicators in the circuits for regulation of control and load disturbances.

2. Tuning of the current control loop

The simplest SO-optimized loop has two integrating units in the control loop, and it is a third-order system with the following normalized transfer function of the optimized open control loop:

$$W_{open}^{SO}(p) = \frac{1}{2T_{mu}p}\frac{1}{T_{mu}p+1}\frac{1+4T_{mu}}{4T_{mu}p} \quad (1)$$

and has two FOTF control objects with $T_a > T_{mu}$:

$$W_{current}(p) = \frac{K_p}{T_{mu}p+1}\frac{K_d}{T_a p+1} \quad (2)$$

2.1. Continuous current mode

In this mode, the control object has a FOTF unit with $K_d = 1/R_a$ and $T_a = L_a/R_a$, and of a FOTF unit (semiconductor converter) with K_p and a small time constant T_{mu}.

2.1.1. Symmetrical optimum tuning – SO tuning. In order to obtain structure (1) from structure (2), it is proposed to perform the control with PI-controller on current with parallel topology with parameters $K_p = T_a/(2T_{mu})$ and $K_i = 1/(2T_{mu})$, with a compensator unit parameters $K_c = 1/K_p/K_d/K_{ov}$ and $W_c(p) = (4T_{mu}p)^{-1} + 1$. K_{ov} is a feedback gain. This control structure is the most complex among the considered objects and it is shown in fig.1.

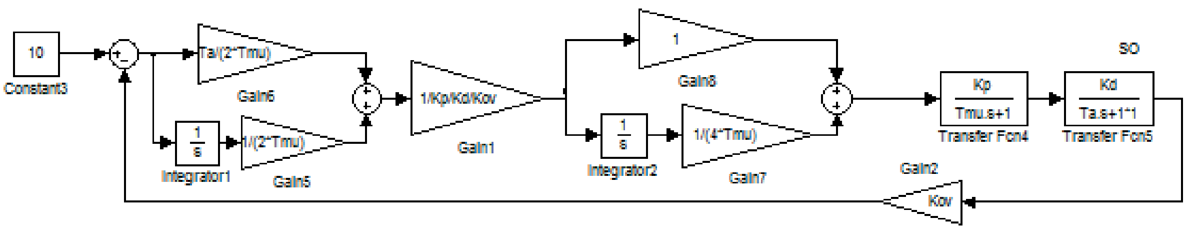

Figure 1.

In practice, in systems with a SO tuning, a FOTF filter with a time constant $T_f = 4T_{mu}$ is included at their input in order to reduce the dynamic loads by reference, while preserving the properties of the control loop.

2.1.2. Technical optimum tuning – TO tuning. The simplest TO-optimized loop has integrating unit in the control loop, and it is a second-order system with the following normalized transfer function of the optimized open control loop:

$$W_{open}^{TO}(p) = \frac{1}{2T_{mu}p}\,\frac{1}{T_{mu}p+1} \tag{3}$$

The transfer function of the control object is the same as in (2).

Therefore, in order to adjust the TO control current loop, it is necessary only to switch off the integral component of the compensator, as shown in fig. 2. The other parameters are the same.

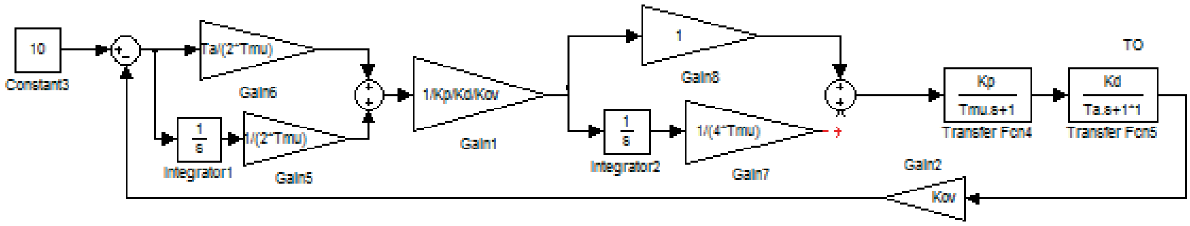

Figure 2.

2.2. Discontinuous current mode

In this mode (d.c.m) Ra increases significantly, $T_a = 0$ and it is assumed that K_d = const. is different from zero.

2.2.1. Symmetrical optimum tuning – d.c.m. SO tuning. Only the proportional component of the controller is excluded from the control structure of fig.1, and it becomes an I-controller with a parameter $K_i=1/(2T_{mu})$. K_d is adjusted to the value of R_a. This structure is shown in fig.3.

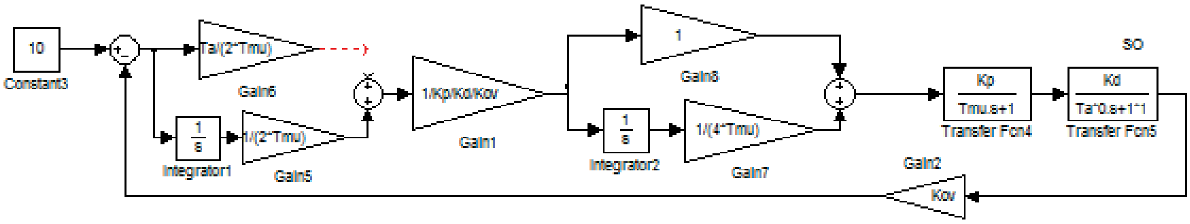

Figure 3.

The actual processes are more complex. They are related to the dependence of R_a on the discontinued current mode and the need to compensate the back-electromotive force (BEMF), but the approach for tuning the current loop is the same.

2.2.2. Technical optimum tuning – d.c.m. TO tuning. In order to switch from a SO tuning to a TO tuning for this mode, it is necessary to switch off (fig.3) the integral component of the compensator, as shown in fig.4.

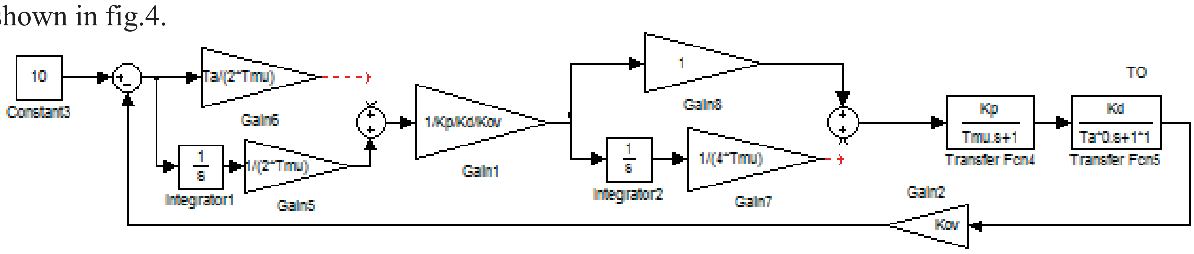

Figure 4.

3. Tuning of the speed control loop

The optimized speed loop must have the transfer function (1) again, however the transfer function of the control object is:

$$W_{speed}(p) = \frac{K_p}{T_{mu}p + 1}\frac{K_d}{T_m p} \quad (4)$$

and has one FOTF unit and one ITF unit.

For convenience in presenting the settings, the designations of the control object are the same as in the previous part 2.

3.1. Symmetrical optimum tuning – SO tuning

In this mode, the control object has an ITF unit with $K_d = 1$ and $K_i = 1/T_m$, $T_m = J.R_a.kfi^{-2}$, and a FOTF unit (optimized current loop!) with a gain K_p and a small time constant T_{mu}. K_{ov} is a feedback gain.

In this case (due to the presence of an integrator unit in the control object) the integral component of the speed controller should be excluded from the structure of fig.1. The other parameters are formally kept the same. This setting is shown in fig.5.

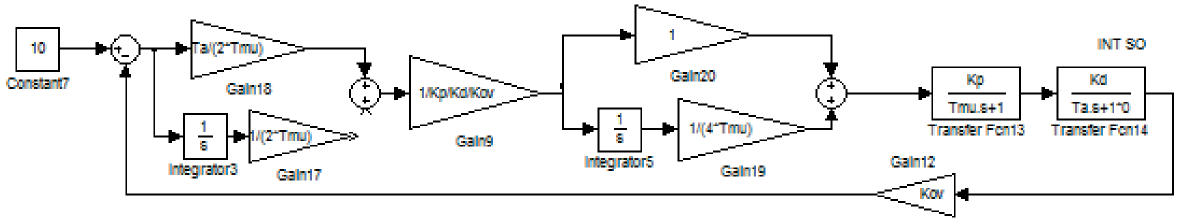

Figure 5.

In practice, in systems with a SO tuning, a FOTF filter with a time constant $T_f = 4T_{mu}$ is included at their input in order to reduce the dynamic loads by reference, while preserving the properties of the control loop.

3.2. Technical optimum tuning – TO tuning

In order to switch from SO tuning to TO tuning, it is necessary to switch off the integral component of the compensator in the control structure (fig.5), as shown in fig.6.

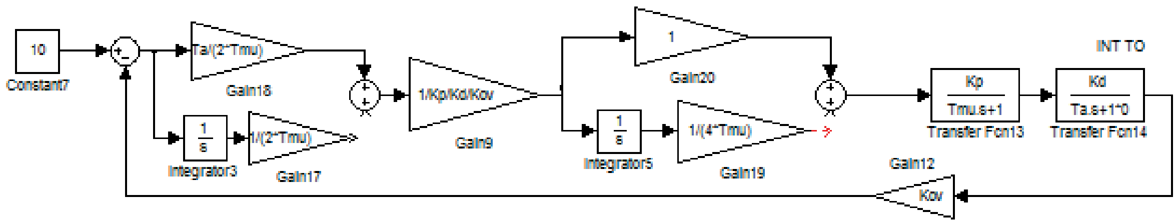

Figure 6.

4. Tuning of the position control loop

The position controler is set similarly to the speed control loop.

5. Methodology of control setting

- For a FOTF object (current control, continuous current mode) the controller is set according to SO tuning (fig.1); for TO tuning of the same object, the integral component of the compensator is switched off (fig.2);

- For a FOTF object (current control, discontinuous current mode, d.c.m.) the controller is set according to SO tuning by switching off the proportional component (fig.3) of the controller; for TO tuning of the same object, the integral component of the compensator is switched off (fig.4);

- For an integrator object (ITF object) (speed and position control) the controller is set according to SO (fig.5) by switching off the integral component of the controller; for TO tuning of the same object the integral component of the compensator is switched off (fig.6);

- The values of the gains K_p, K_d and K_{ov} are included in the control as a constant part with gain $K_{sum} = 1/K_p/K_d/K_{ov}$.

The proposed methodology is systematized, described and shown in the table.

Control parameter tuning

Object \ Control Unit		SO	TO
Current	Controller	$K_p=T_a/2T_{mu}$ ($K_p=0$ for d.c.m.) $K_i=1/2T_{mu}$	$K_p=T_a/2T_{mu}$ ($K_p=0$ for d.c.m.) $K_i=1/2T_{mu}$
	K_{sum}	$K_{sum}=1/K_p/K_d/K_{ov}$	$K_{sum}=1/K_p/K_d/K_{ov}$
	Compensator	$K_c=1$ $1/T_c=1/4T_{mu}$	$K_c=1$ $1/T_c=0$
	FOTF Filter	$T_f=4T_{mu}$	$T_f=0$
Speed	Controller	$K_p=T_m/4T_{mu}$ $K_i=0$	$K_p=T_m/4T_{mu}$ $K_i=0$
	K_{sum}	$K_{sum}=1/K_p/K_d/K_{ov}$	$K_{sum}=1/K_p/K_d/K_{ov}$
	Compensator	$K_c=1$ $1/T_c=1/8T_{mu}$	$K_c=1$ $1/T_c=0$
	FOTF Filter	$T_f=8T_{mu}$	$T_f=0$
Position	Controller	$K_p=1/8T_{mu}$ $K_i=0$	$K_p=1/8T_{mu}$ $K_i=0$
	K_{sum}	$K_{sum}=1/K_p/K_d/K_{ov}$	$K_{sum}=1/K_p/K_d/K_{ov}$
	Compensator	$K_c=1$ $1/T_c=1/16T_{mu}$	$K_c=1$ $1/T_c=0$
	FOTF Filter	$T_f=16T_{mu}$	$T_f=0$

Models have been synthesized in Simulink [7], for the tuning of the controllers according to fig.1-fig.6 with m-files with the following parameters: $K_p=22$; $R_a=0.2$ Ohm; $K_d=1/R_a$ Ohm^{-1}; $K_{ov}=0.25$; $T_a=0.015$ s; $T_{mu}=0.0015$ s.

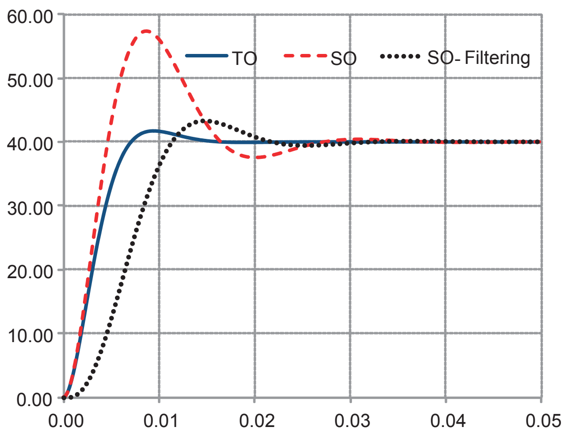

Figure 7.

6. Verification

The models from fig.1 to fig.4 are verified through the transient processes shown in fig.7 on SO, TO, and SO with included filter at the input and with a filter time constant $T_f = 4T_{mu}$ for current control loop. The current reference is 40 A, the scale on the time axis is in seconds.

The behavior of the optimized control loops fully corresponds to the indicators of the TO tuning, the SO tuning, and to the SO tuning with a switched on FOTF input filter.

Acknowledgments

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References

[1] Karl Johan Åström and Richard M. Murray (2008), Feedback Systems: An Introduction for Scientists and Engineers, Princeton University Press, ISBN 9780691135762, Pages: 408.

[2] Bolton W., Mechatronics. Electronic Control Systems In Mechanical And Electrical Engineering, Sixth Edition, Pearson Education, 2015, p.663, ISBN 978-1-292-08159-5.

[3] Liuping Wang, Shan Chai, Dae Yoo, Lu Gan and Ki Ng, PID and Predictive Control of Electrical Drives and Power Converters using MATLAB®/Simulink®, First Edition, 2015, John Wiley & Sons Singapore, ISBN: 9781118339442, Pages: 344.

[4] Krishnan R., Electric Motor Drives. Modeling, Analysis, and Control, Singapore, 2003, ISBN 81-297-0319-1, pp.650.

[5] Kessler C. (1955). Uber die Vorausberechnung optimal abgestimmter Regelkreise. Teil III. Die optimale Einstellung des Reglers nach dem Betragsoptimum. Regelungstechnik.–B.3.–H. 2.–S.40–49.

[6] Kessler C. (1958). Das symmetrische Optimum. Teil I und III. Regelungstechnik. – B. 6.– H.11.– S. 395–400; H.12.– S.432–436.

[7] http://www.mathworks.com.