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# Selection of a Drive Controllers' Parameters Using Genetic Algorithm and Different Quality Criteria

***Abstract**. Classic methods for control systems design consist in fulfilling given design objectives, e.g.: requirements for the system stability, overshoot of step response or closed-loop system poles location. It is difficult to take simultaneously into account all design requirements because of various compromises that should be made in the design process and the design technique constraints. The paper presents a possibility of employing artificial intelligence methods, in the form of genetic algorithm, as a tool for optimisation of parameters of DC drive controllers based on the drive model with minimum simplifications and taking into account nonlinear components. An additional merit of this work is comparison of drive controls according to various quality criteria, as well as the combination of these criteria. It seems that genetic algorithms can be successfully applied to optimisation controllers' parameters settings.*

***Streszczenie.** Klasyczna metoda projektowania układów sterowania polega na spełnieniu odpowiednich założeń projektowych np. wymagania odnośnie stabilności układu, zadanego przeregulowania odpowiedzi na wymuszenie skokowe lub położenia biegunów układu zamkniętego. Uwzględnienie wszystkich założeń projektowych jednocześnie jest trudne z powodu różnorodności kompromisów, które należy dokonać podczas projektowania, oraz ograniczeń techniki projektowania. W niniejszym artykule zaprezentowano możliwość wykorzystania metod sztucznej inteligencji w postaci algorytmu genetycznego jako narzędzia do optymalizacji nastaw regulatorów silnika obcowzbudnego prądu stałego na podstawie jego modelu z minimalną liczbą uproszczeń oraz z elementami nieliniowymi. Dodatkową zaletą pracy jest zestawienie sterowania silnikiem według różnych kryteriów jakości jak również przy złożeniu tych kryteriów.(**Dobór parametrów regulatorów silnika obcowzbudnego z użyciem algorytmu genetycznego dla różnych kryteriów jakości**)*

**Keywords**: DC motor drive, genetic algorithms, optimization methods, multi criteria optimization.
**Słowa kluczowe**: napęd prądu stałego, algorytm genetyczny, metody optymalizacji, optymalizacja wielokryterialna.

## Introduction

The Kalman's LQG theory was a milestone on the way to development of control methods [1]. The key advantage of this design method is the use of mathematical model of a controlled object of research. Modelling is a difficult and time-consuming process that requires simplifications. This is the reason for a major discrepancy between the chosen (assumed) model and the actual system.

Recently the $H_\infty$ control theory has taken into account the problem of system robustness [2] - [9]. This method, employing a mathematical model, allows designing a linear system control that limits the influence of undesired (disturbing) signals. Development of a controlled plant model is based on simplifying assumptions and linearization. The method of seeking the controllers' settings by means of genetic algorithm may not suffer from that drawback, i.e. the number of simplifications and linearizations can be limited to minimum or can be avoided. Genetic algorithms are increasingly used to solve various optimization problems [10] – [15]. Examples of controls of electric drive including the use of artificial intelligence methods can be found in various articles [16] – [19]. The intention of this article is to present a new method of designing with AG at the same time reduce the number of simplifications as well as various quality criteria.

## Controller according to Kessler

The separately excited motor rotational speed can be controlled using a control system with two control loops [20]. The system diagram is shown in Fig. 1.

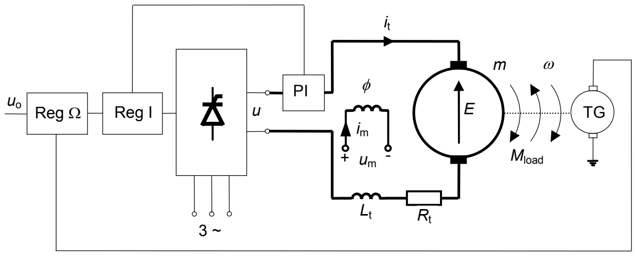


Fig. 1. Schematic diagram of DC drive control with two control loops: PI – current measuring unit; TG – tachogenerator; Reg I – current controller; Reg Ω - speed controller

The system depicted in Fig. 1 exhibits sufficient dynamic properties (the drive response to change in reference signal and to change in the load torque) with limited maximum absolute value of the armature current. The type of controllers and their settings are selected based on the modulus optimum criterion and symmetrical optimum criterion (according to Kessler). DC motor is described by equations:

$$u = R_t i + L_t \frac{di}{dt} + k\omega$$
$$m = M_{load} + J\frac{d\omega}{dt} \qquad (1)$$
$$m = ki$$

where: $u$ – armature voltage, $R_t$ – armature resistance, $I$ – armature current, $L_t$ – armature inductance, $k$ – constant coefficients dependent on the motor structure and excitation current, in the SI units system it is the flux linkage, $m$ – electromagnetic torque, $M_{load}$ – mechanical load torque, $J$ – moment of inertia referred to the motor shaft, $\omega$ – the motor angular speed.

A thyristor converter can be regarded (making a simplification) as a first-order inertial element with the transmittance:

$$G_p = \frac{K_p}{1 + sT_p} \qquad (2)$$

where: $K_p$ – the converter gain, $T_p$ – the converter time constant.

The following controllers' structures are assumed:
- the speed controller (PI)

$$G_\Omega(s) = \frac{1 + sT_1}{sT_2} \qquad (3)$$

- the current controller (PI)

$$G_I(s) = \frac{1 + sT_3}{sT_4} \qquad (4)$$

where: $T_1$, $T_2$, $T_3$, $T_4$ – controllers' settings.

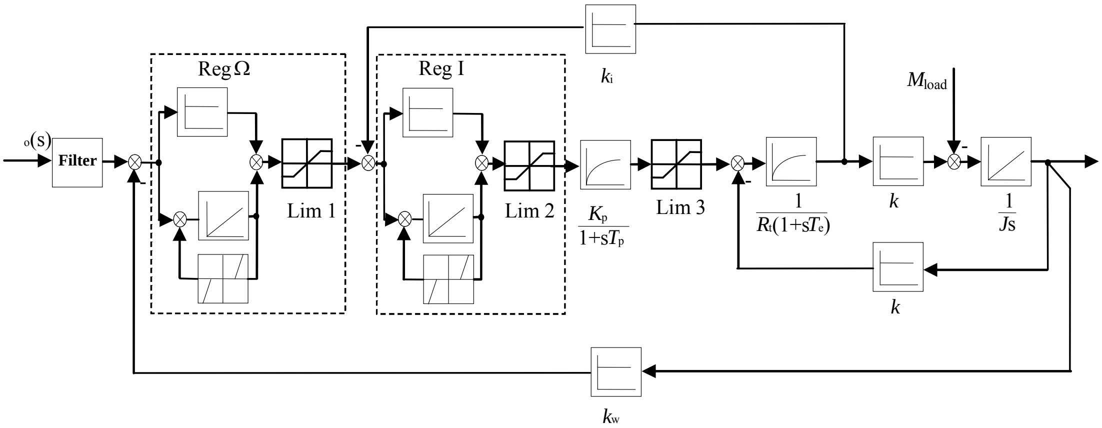


Fig. 2. block diagram of the DC drive system with secondary control loops: $k_w$ –speed measuring loop gain, $k_i$ –current measuring loop gain, $\Omega_o$ - speed reference signal

Electric drive control systems with two control loops employ electronic (analogue) controllers or, presently more frequently, programmable (digital) controllers. Both the current and speed controller have limitation of the output signal maximum value. Also the converter maximum output voltage is limited (it cannot exceed the maximum available value corresponding to the full control angle).

The block diagram of the chosen system shown in Fig. 1 is depicted in Fig. 2.

The chosen system does not have robustness properties (robustness to disturbance signals and unmodelled dynamics in the $H_\infty$ norm sense). A system modelling most often consists in linearization of nonlinear parts, disregarding constraints and introducing other simplifications that allow choosing the model in the form of linear differential equations. A model defined in that manner is the source of discrepancy between the model behaviour and reality (the simulation and actual results). The controller designed for a simplified model may not co-operate properly with the actual system. Hence it could be concluded that in order to ensure a proper operation of the controller designed with classic methods, the mathematical model of the controlled plant should be accurate (i.e. precisely represent the real plant), otherwise its inaccuracy would give rise to errors.

For simulation purposes has been chosen the separately excited motor with parameters:

$P_N$ = 22 kW, $U_N$ = 440 V, $I_N$ = 56.2 A, $J$ = 2.7 kg·m$^2$, $R_t$ = 0.465 Ω, $L_t$ = 15.345 mH, $n_N$ = 1500 rpm, $k$ =2.62,

$\omega_N = \frac{\pi n}{30} = 157\ \frac{1}{s}$, (subscript N – nominal)

The converter and PI controllers' parameters according to the Kessler criterion are: $K_p$ = 100, $T_p$ =1.67·10$^{-3}$ s, $k_i$ = 0.1, $k_w$ = 0.05, $T_1$ = 0.15 s, $T_2$ = 2.65·10$^{-3}$ s, $T_3$ = $T_e$ = 33·10$^{-3}$ s, $T_4$ = 0.215 s

The motor speed reference signal is defined as:

$$u_0(t) = \begin{cases} \alpha t + U_{0\min} & \text{for} \quad t \le t_1 \\ U_{0\max} & \text{for} \quad t > t_1 \end{cases} \tag{5}$$

where: $U_{0max}$ = 7.25 V, $U_{0min}$ = 0.05·$U_{0max}$, $t_1$ = 0.9 s,
$\alpha$ = ($U_{0max}$ - $U_{0min}$)/$t_1$ = 7.65 V/s

At start-up the motor is loaded with constant torque of 140 N·m that after 3 seconds is reduced to 60 N·m.

Figures 3 and 4 show the simulation results: the reference signal $u_0$, the armature current signal $i$, the motor rotational speed $\omega(t)$ and the difference between the set and actual motor speed $\Delta\omega$, for the case the controllers are designed according to the Kessler criterion. In a short time the starting current attains a large value, then slightly decreases and stabilizes at ca. 210 A for a period of about 1s. The end of starting time is marked by the current decrease to about 50 A, until the change in the load torque that results in the current reduction to ca. 25 A. The change in the motor speed caused by the load change at $t$ = 3 s, is small and temporary.

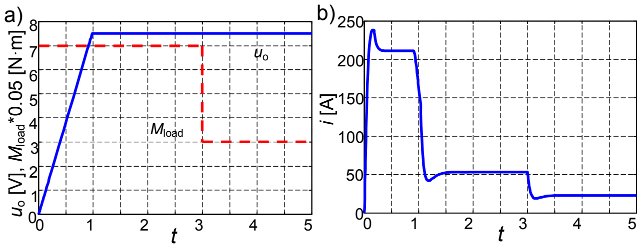


Fig. 3. Time plots of: a) the reference signal $u_0$ and mechanical torque, b) the armature current

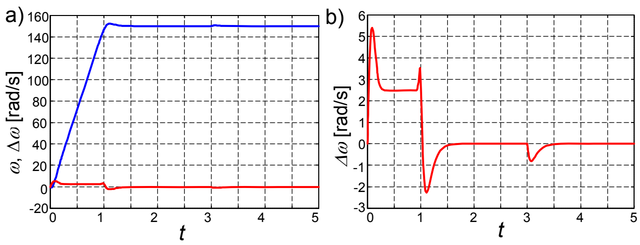


Fig. 4. Time plots of: a) the motor speed signal $u_0$, b) the difference between the set and actual motor speed

## $H_\infty$ norm control

Generally, the optimal control of a linear dynamic system by means of a linear controller reduces to minimization of a certain norm of the closed-loop system transmittance. Various norms can be induced by different assumptions on the system physical properties and signals acting upon it. Therefore, the optimal control reduces to seeking, within the set of controllers stabilizing the system, for a controller such that the norm of the closed-loop system is minimum. The linear-quadratic problem, posed in the late fifties and intensively developed during two following decades, has played a significant role in the control theory development.

From the theoretical point of view, the linear-quadratic problem (and its variants) offers a uniform and coherent mathematical apparatus together with numerical solution procedures in the form of CAD software. However, the linear-quadratic control theory does not account for the system uncertainty and measurement noise. Moreover, in order to compute controls the full state vector is required. The response to these inconveniences was Kalman and

Bucy work [1] introducing the Wiener filter version in the state space. This version enabled optimal estimation of the system state based on the system noisy outputs and solved the problem of the knowledge of state. On the other hand, Doyle [4] has demonstrated that a system optimised that way may have an arbitrary narrow stability margin. At the early eighties these results had lead to application of Hardy space (with supremum norm) to the problem of linear system optimal control.

The problem of linear system optimal control, due to the quadratic quality index in an incomplete system state and noisy output is known as the linear-quadratic-Gaussian (LQG) problem. In this case optimal control is a linear function state estimate obtained from the Kalman filter.

The ultimate objective of design is to develop a controlling system that would work correctly in a real system. Since the environment changes over time (ageing of components, influence of temperature or other ambient factors) or operating conditions are varying (modifications, disturbances), the control system shall be able to withstand these changes. Another thing is the uncertainty of modelling – the mathematical representation of a system often requires simplification of assumptions. Certain parts of the system, although they may be variable or nonlinear, are sometimes modelled by a constant gain coefficient. Dynamic structures exhibit complex dynamic behaviour at high frequencies, which is neglected in the design phase. Since controllers are usually designed employing a grossly simplified model of the controlled system (plant), they may not work properly in a real control system or in a real environment. In order to operate correctly under real conditions the control system must have the property referred to as robustness. Thus the design objective is not the stability itself but the robustness; stability must be maintained despite of the model uncertainty.

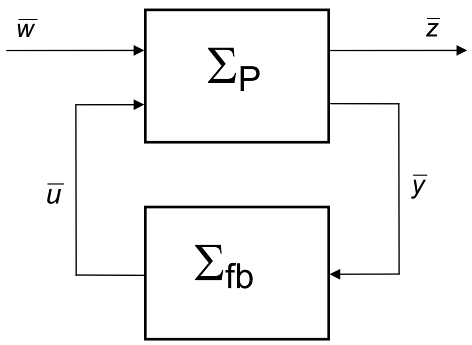


Fig. 5. Basic concept of system controlled according to $H_\infty$ norm

After a period of fascination came a slight disappointment that resulted in a new approach to the problem – the $H_\infty$ control, posed by George Zames [21], initially exclusively in the frequency domain. $H_\infty$ norm control is based on the system description in the two-port system form, as shown in Fig. 5.

Given is a finite-dimensional, time invariant, linear system $\Sigma_P$ with dynamic properties described by the following equations:

$$(6)\qquad \Sigma_P : \begin{cases} \dot{\overline{x}} = \boldsymbol{A}\overline{x} + \boldsymbol{B}_1\overline{w} + \boldsymbol{B}_2\overline{u} \\ \overline{z} = \boldsymbol{C}_1\overline{x} + \boldsymbol{D}_{11}\overline{w} + \boldsymbol{D}_{12}\overline{u} \\ \overline{y} = \boldsymbol{C}_2\overline{x} + \boldsymbol{D}_{21}\overline{w} + \boldsymbol{D}_{22}\overline{u} \end{cases}$$

where: $\overline{x}$ - state variables, $\overline{w}$ - egzogenic inputs, $\overline{u}$ - input reference signals, $\overline{z}$ - controlled output signals, $\overline{y}$ - measurement-accessible output signals.

The standard $H_\infty$ control problem could be formulated as follows: for a given linear system (described by equations (6) and an arbitrarily chosen number $\gamma > 0$, should be found a finite-dimensional, time invariant controller $\Sigma_{fb}$, such that closed-loop system will be stable and the norm $H_\infty$ will be less than $\gamma$.

Such control can be found by solving two algebraic Riccati equations (assuming the solution exists). The controller designed that way ensures the system robustness (within a limited range) to noise, disturbances and unmodelled system dynamics that affect the system operation.

Figures 6 and 7 illustrate time-plots of signals recorded during simulation of the separately excited motor (in Fig. 1) with $H_\infty$ controller.

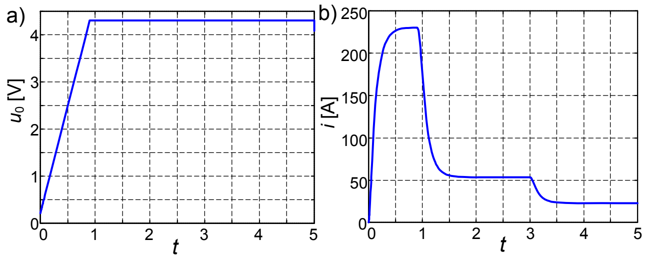


Fig. 6. Time plots of: a) the reference signal $u_0$, b) the armature current

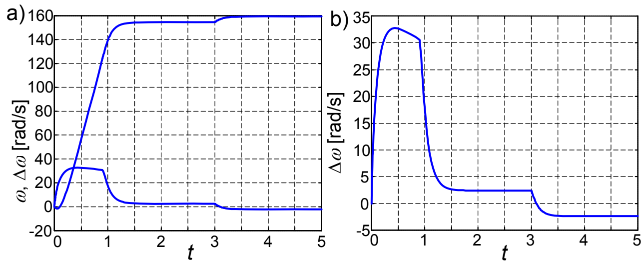


Fig. 7. Time plots of: a) the motor speed signal $u_0$, b) the difference between the set and actual motor speed

The armature current rate-of-rise is lower than that in the case of the control using controllers designed according to the Kessler criterion, a change in the load torque results in constant change in the motor speed and the difference between the set and actual motor speed is grater than that in the classic control.

## Controllers Optimisation Using Genetic Algorithm

For a DC drive with cascade controlling system as shown in Fig. 1, the settings of the current and speed controllers were determined minimizing the following three quality criteria [20]:

1. the sum of squares of the motor speed error: $\int_{t=0}^{5} e^2 \mathrm{d}t$
2. maximum of the modulus of the system spectral transmittance from disturbance variables inputs (the load torque and measuring feedback noise) to the output represented by the motor speed: $\max(|G(\mathrm{j}\omega)|)$
3. the sum of the two above indices: $\int_{t=0}^{5} e^2 \mathrm{d}t + \max(|G(\mathrm{j}\omega)|)$

To all these indices, that became the genetic algorithm objective functions, were applied genetic algorithms of the identical structure:

- the variability range of decision variables: $T_1$, $T_2$, $T_3$, $T_4$ = (0 – 50000).

- each parameter is encoded into a 20-bit sequence, i.e. a chromosome length is 80 bits,
- population size 200 individuals,
- probability of crossover $p_k$ = 0.7,
- probability of mutation $p_m$ = 0.035,
- termination condition – 30 populations,
- ranking with coefficients $C_{min}$ = 0, $C_{max}$ = 2,
- sorting in the reverse order to minimize the objective function,
- stochastic universal selection (SUS),
- shuffle crossover.

Table 1. Controllers' settings obtained by means of the genetic algorithm minimizing three indices

| Index | $T_1$ s | $T_2$ s | $T_3$ s | $T_4$ s |
|---|---|---|---|---|
| $\sum_{t=0}^{5} e^2$ | 2.74 | 0.0034 | 4 | 2.42 |
| $\max(\lvert G(j\omega)\rvert)$ | 49974 | 22879 | 58 | 17 |
| $\sum_{t=0}^{5} e^2 + \max(\lvert G(j\omega)\rvert)$ | 47349 | 134.6 | 36273 | 14189 |

Figure 8 summarises time-plots of the motor current and speed obtained during simulation of the motor control system with controllers designed by means of the genetic algorithm subsequently optimising three quality indices.

Controllers' settings, obtained by means of the genetic algorithm subsequently minimizing three predefined indices, are listed in Table 1.

Table 2 provides indices of the motor speed error indices and $H_\infty$ norms obtained for the DC motor control system with controllers designed employing various norms, including also the genetic algorithm.

Table 2. Indices of the motor speed error and $H_\infty$ norm for various optimization criteria

| | Method of selection controllers' settings | $\sum_{t=0}^{5} e^2$ | $\max(\lvert G(j\omega)\rvert)$ |
|---|---|---|---|
| classic criteria | Kessler | 849.29 | 348 |
| | $H_\infty$ | 36733 | 0.3816 |
| Genetic Algorithm | $\min\left(\sum_{t=0}^{5} e^2\right)$ | 52.1 | 1122 |
| | $\min(\max(\lvert G(j\omega)\rvert))$ | 21568 | 1.0003 |
| | $\min\left(\sum_{t=0}^{5} e^2 + \max(\lvert G(j\omega)\rvert)\right)$ | 386.86 | 171 |

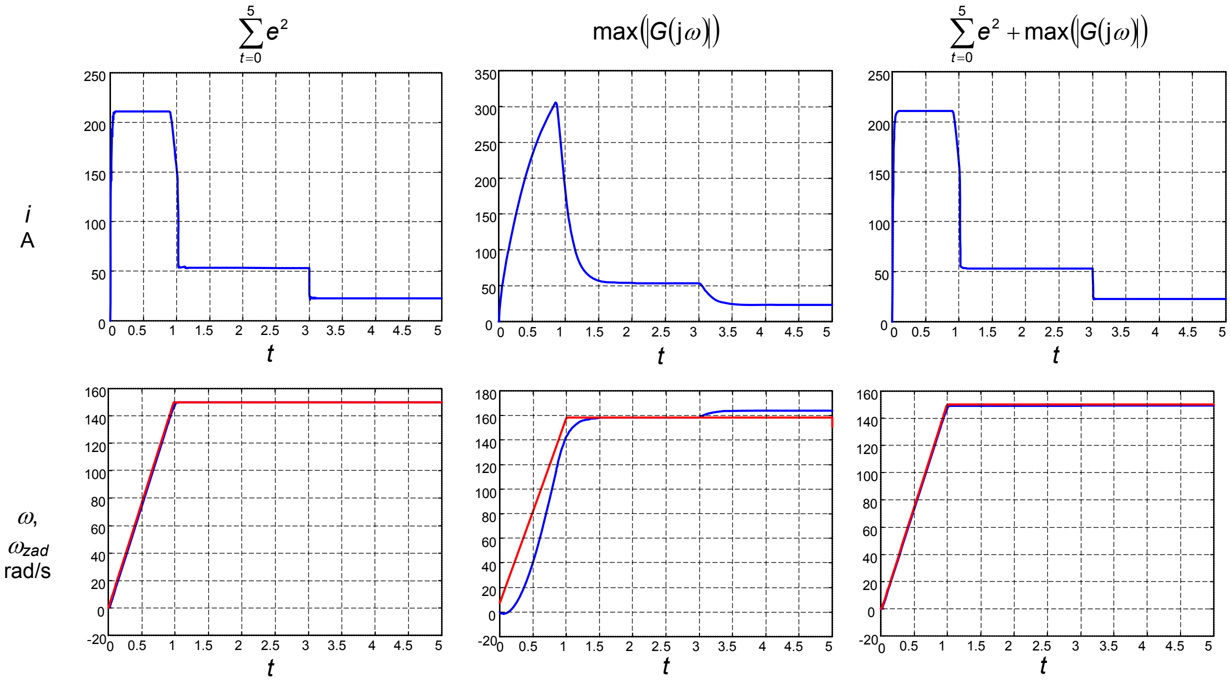


Fig. 8. The armature current and motor speed time-plots obtained during simulation of the motor control system with controllers optimised according to the subsequent quality indices

Figure 9 summarises time-plots of the motor speed error in response to the speed reference. The results are grouped on two diagrams according to criteria optimised by the genetic algorithm.

While minimizing the sum of the speed error and $H_\infty$, the obtained speed time-plots are closer to the reference trajectory than those obtained when solely the $H_\infty$ norm is optimised using classic method and by means of the genetic algorithm as well as those obtained when the controllers are optimised using the Kessler method.

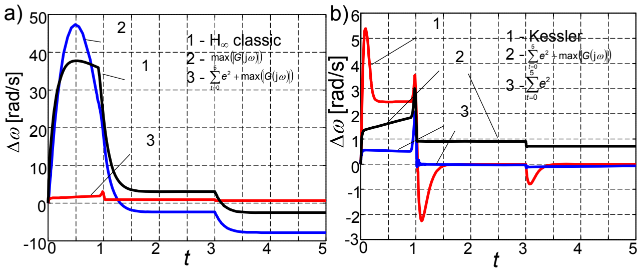


Fig 9. Summary of the motor speed error optimised according to norms indicated on the plots

The values of indices listed in Table 2 show that combination of the speed error indices and $H_\infty$ norm gave positive results that combine the advantages of optimisation according to each criterion individually.

### Experimental Verification

The conclusions drawn from computer simulations have been confirmed in the controllers' settings optimisation by means of the genetic algorithm for a laboratory DC drive [20] (Fig. 10).

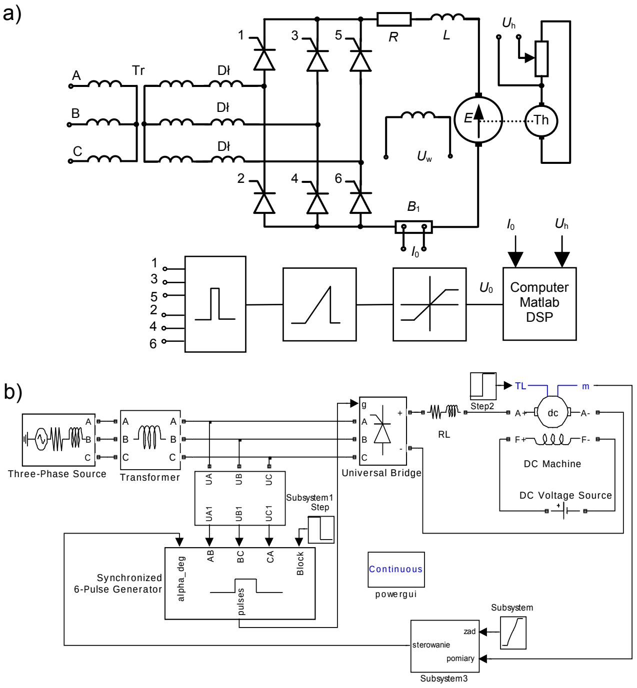


Fig. 10. Diagram of the separately excited motor control system (a) and its Matlab model (b)

Table 3. A summary of controllers' parameters determined by the genetic algorithm for different optimisation criteria

| criterion | $T_1$ | $T_2$ | $T_3$ | $T_4$ | Norm $e^2$ | Norm $H_\infty$ |
|---|---|---|---|---|---|---|
| min(max($G(j\omega)$)) | 1.18 | 0.8 | 2 | 0.4 | 225 | 1.1 |
| min($e^2$+max($G(j\omega)$)) | 5.1 | 14.9 | 64.7 | 32.9 | 8.1 | 5.09 |
| min($e^2$) | 22.3 | 8.6 | 80.4 | 17.6 | 1.12 | 11 |

The genetic algorithm performed offline optimisation of controllers' settings basing on Matlab model of the real plant. The optimisation was performed according to the three criteria: $e^2$, $H_\infty$ and ($e^2$ + $H_\infty$). Running the genetic algorithm three times with different objective functions gave different values of PI controllers' parameters. Their values are provided in table 3.

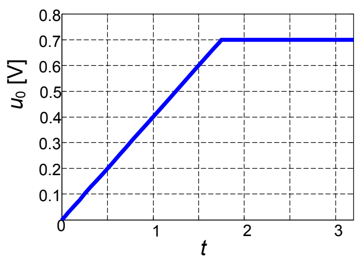


Fig. 11. The motor speed reference signal

Figure 11 shows the DSP generated reference signal. The current (a) and motor speed (b) signals after optimisation according to the $e^2$ criterion are shown in Fig. 12. In the initial phase the motor starting current attains its maximum value and than it undergoes further changes. The speed follows the reference signal fairly accurately.

Characteristics obtained in result of $H_\infty$ norm optimisation are shown in Fig. 13. The current value (a) is changing slowly and the speed (b) slowly follows the reference signal. The system has robustness properties, i.e. noise and disturbances affect the system operation only to a limited extent.

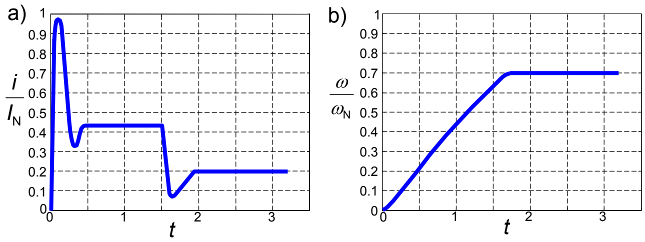


Fig. 12. The motor current (a) and speed (b) after optimisation according to the $e^2$ criterion

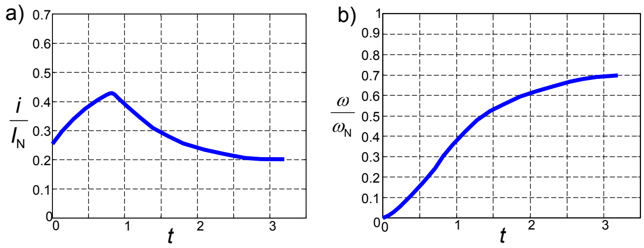


Fig. 13. The motor current (a) and speed (b) after optimisation according to $H_\infty$ norm

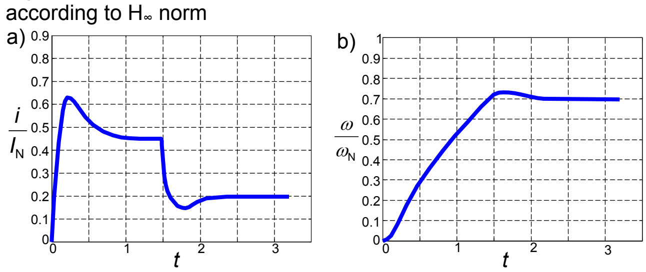


Fig. 14. The motor current (a) and speed (b) after optimisation according to the sum of both norms

Time-plots in Fig. 14 illustrate the motor current (a) and speed (b) after optimisation according to the sum of the $e^2$ and $H_\infty$ norms. As follows from figure a compromise has been achieved between the speed and accuracy of the controlling system operation and its robustness to noise and disturbances in the system, as well as robustness to unmodelled dynamics resulting from simplifications made in the design phase.

### Conclusions

The work has demonstrated the possibility of employing an artificial intelligence method, i.e. the genetic algorithm, for optimisation of parameters of DC separately excited motor controllers, based on the motor model comprising nonlinear components and using different quality criteria, as well as the combination of these criteria being a compromise between them. That tool allows us to reduce the number of the necessary model simplifications and create an arbitrary control quality criterion. Its additional advantage is the possibility of introducing at the same time limitations (e.g. maximum starting current) to optimisation. It seems that genetic algorithms can be successfully applied to optimisation controllers' parameters settings.

It has also been demonstrated that a compromise between the control criteria (i.e. minimum error and robustness criterion) can be found in order to combine the advantages of both criteria.

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