Slovak University of Technology in Bratislava
Institute of Information Engineering, Automation, and Mathematics

PROCEEDINGS

17$^{\mathrm{th}}$ International Conference on Process Control 2009

Hotel Baník, Štrbské Pleso, Slovakia, June 9 – 12, 2009

ISBN 978-80-227-3081-5

http://www.kirp.chtf.stuba.sk/pc09

Editors: M. Fikar and M. Kvasnica

Kozáková, A., Osuský, J., Veselý, V.: Tuning Decentralized Controllers for Robustness and Performance, Editors: Fikar, M., Kvasnica, M., In *Proceedings of the 17th International Conference on Process Control '09*, Štrbské Pleso, Slovakia, 368–374, 2009.

Full paper online: http://www.kirp.chtf.stuba.sk/pc09/data/abstracts/089.html

TUNING DECENTRALIZED CONTROLLERS FOR ROBUSTNESS AND PERFORMANCE

Alena Kozáková, Jakub Osuský and Vojtech Veselý

Faculty of Electrical Engineering and Information Technology
Slovak University of Technology in Bratislava, Slovak Republik
Email: alena.kozakova@.stuba.sk, jakub.osusky@stuba.sk

Abstract: The paper presents a modification of the decentralized controller design technique for continuous-time systems (named "Equivalent Subsystems Method", ESM) proposed in (Kozáková and Veselý, 2003; 2007) and further developed towards securing robust stability and nominal performance (Kozáková and Veselý, 2005; 2006). The proposed design procedure combines the ESM with a subsequent detuning to fulfil the M-Δ structure robust stability conditions adapted for the decentralized control. Robust decentralized controllers designed for two real plants show practical applicability of the proposed design philosophy.

Keywords: decentralized control, detuning, nominal stability, robust stability, unstructured uncertainty

1. INTRODUCTION

Many industrial processes are naturally multi-input multi-output (MIMO) as they arise as interconnection of a finite number of physically existing subsystems. Due to the interactions, MIMO systems are more difficult to control compared with the SISO ones. Multivariable controllers are used if strong interactions within the plant are to be compensated for. Decentralized controllers remain popular in the industry when practical reasons make restrictions on controller structure necessary or reasonable. Compared with centralized full-controller systems the decentralized control (DC) structure brings about certain performance deterioration; however weighted against important benefits, e.g. hardware, operation and design simplicity, and reliability improvement Therefore, decentralized control (DC) design techniques remain popular among practitioners, in particular the frequency domain ones which provide insightful solutions and link to the classical control theory.

Since the 80's several practice-oriented robust control design techniques have evolved differentiating in the design of local SISO controllers the main approaches being simultaneous design, independent design e.g. (Hovd and Skogestad, 1993; Kozáková, 1998) and sequential design e.g. (Hovd and Skogestad, 1994). The method proposed in this paper belongs to the independent design according to which local controllers are designed independently without considering interactions with other subsystems. Main advantages with this approach are failure tolerance and direct local designs, the main limitation is that information about controllers in other loops is not exploited; therefore obtained stability and performance conditions are only sufficient and thus conservative.

The paper deals with a further improvement of the robust decentralized controllers design technique for continuous-time uncertain systems (so-called "Equivalent Subsystems Method") first proposed as a DC design method for performance (Kozáková and Veselý, 2003) and further adapted so as to simultaneously guarantee nominal performance and fulfilment of the M-Δ structure based robust stability conditions modified for the closed-loop under the decentralized controller (Kozáková and Veselý, 2005; 2006; Veselý and Kozáková, 2005a; 2005b). This design technique considers the full transfer function matrix nominal system - unlike the existing robust DC approaches which take as nominal system just the diagonal part of the plant transfer matrix.

The paper is organized as follows: theoretical background and problem formulation are given in Section 2, development of the robust decentralized controller design technique is presented in Section 3 and illustrated by two examples in Section 4. Conclusions are given at the end of the paper.

2. THEORETICAL BACKGROUND PROBLEM FORMULATION

Consider a plant transfer function $G(s) \in R^{m\times m}$ and a diagonal controller $R(s) \in R^{m\times m}$ in a standard feedback configuration (Fig.1) where w, u, y, e, d are vectors of reference, control, output, control error and disturbance, respectively, of compatible dimensions.

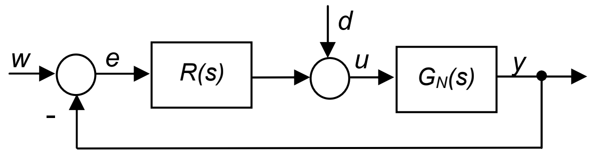

Fig. 1 Standard feedback configuration

Let the uncertain plant model be given as a set of N transfer function matrices in N different operating points, hence

$$G^k(s) = \{G_{ij}^k(s)\}_{m\times m},\ k = 1,2,\ldots,N \qquad (1)$$

with $G_{ij}^k(s) = \dfrac{y_i^k(s)}{u_j^k(s)}, \quad i,j = 1,2,\ldots,m$

where $y_i^k(s)$ is the *i-th* output and $u_j^k(s)$ is the *j-th* input of the plant in the *k-th* experiment.

In this paper, unstructured uncertainty associated with the system model (1) will be described using additive (a), multiplicative input (i) and multiplicative output (o) forms, generating the related families of plants $\Pi_i,\ i = a,i,o$:

$$\Pi_a :\ G(s) = G_N(s) + \ell_a(s)\Delta(s) \qquad (2)$$

$$\ell_a(s) = \max_k \sigma_M[G^k(s) - G_N(s)]$$

$$\Pi_i :\ G(s) = G_N(s)[I + \ell_i(s)\Delta(s)] \qquad (3)$$

$$\ell_i(s) = \max_k \sigma_M\{(G^k(s))^{-1}[G^{-1}(s) - G_N(s)]\}$$

$$\Pi_o :\ G(s) = [I + \ell_o(s)\Delta(s)]G_N(s) \qquad (4)$$

$$\ell_o(s) = \max_k \sigma_M\{[G_N(s) - G^k(s)](G^k(s))^{-1}\}$$

where $G_N(s)$ denotes the nominal model, $\sigma_M(\cdot)$ is the maximum singular value of *(.)* and $\Delta(s) \in R^{m\times m}$ is uncertainty matrix such that $\sigma_M(\Delta) \le 1$.

Standard feedback configuration comprising the uncertain system can be transformed into the $M-\Delta$ structure; for individual uncertainty types the corresponding matrices M_k, $k=a,i,o$ are as follows (Skogestad and Postlethwaite, 1996):

$$M_a = -\ell_a(s)[I + R(s)G_N(s)]^{-1}R(s)$$
$$M_i = -\ell_i(s)[I + R(s)G_N(s)]^{-1}R(s)G_N(s) \qquad (5)$$
$$M_o = -\ell_o(s)G_N(s)R(s)[I + G_N(s)R(s)]^{-1}$$

Robust stability conditions in terms of the $M-\Delta$ structure are given in the following theorem.

Theorem 1 (Robust stability for unstructured perturbations)
Assume that the nominal system $M_k(s),\ k = a,i,o$ is stable and the perturbations $\Delta(s)$ are stable. Then the $M-\Delta$ system is stable for all perturbations satisfying $\sigma_M[\Delta(j\omega)] \le 1$ if and only if

$$\sigma_M[M_k(s)] < 1,\ \ \forall s \qquad (6)$$

Nominal closed-loop stability of a MIMO system can be examined using the generalized Nyquist stability theorem.

Theorem 2 (Generalized Nyquist Stability Theorem)
The feedback system in Fig. 1 is stable if and only if

$$\left.\begin{array}{l} 1.\ \ det\,F(s) \ne 0 \qquad \forall s \in D \\ 2a.\ \ N[0, det\,F(s)] = n_q \\ \text{or} \\ 2b.\ \ \sum_{i=1}^{m} N\{0,[1 + q_i(s)]\} = n_q \end{array}\right\} \qquad (7)$$

where $Q(s) = G_N(s)R(s)$ is the open-loop matrix, n_q is the number of its right half-plane poles, $det\,F(s) = det[I + Q(s)]$ is the closed-loop characteristic polynomial, $N[0, det\,F(s)]$ is the number of anticlockwise encirclements of the point *(0, j0)* by the Nyquist plot of *detF(s)*. $q_i(s),\ i = 1,2,\ldots,m$ are the set of characteristic loci (CL) of *Q(s)* in the complex plane (MacFarlane and Postlethwaite, 1977).

Problem Formulation.

Consider an uncertain MIMO system with m subsystems (1). A robust decentralized controller

$$R(s) = diag\{R_i(s)\}_{i=1,\ldots,m} \qquad (8)$$
$$det\,R(s) \ne 0 \quad \forall s$$

is to be designed with $R_i(s)$ being transfer function of the *i-th* local controller. The designed controller has to guarantee stability and an acceptable performance of the controlled plant within the entire plant operating range described using either of the perturbed models (2), (3) or (4).

3. DEVELOPMENT OF THE ROBUST DC DESIGN METHOD

Consider the nominal model $G_N(s) \in R^{m \times m}$ split into the diagonal and the off-diagonal parts describing respectively models of decoupled nominal subsystems and nominal interactions $G_m(s)$

$$G_N(s) = G_d(s) + G_m(s) \quad (9)$$

where $G_d(s) = diag\{G_i(s)\}_{i=1,...,m}$ and

$det\, G_d(s) \neq 0 \quad \forall s \in D$.

Factorize the nominal closed-loop characteristic polynomial $det\, F(s)$ in terms of the split nominal system (Kozáková and Veselý, 2003; 2007)

$$\begin{aligned} det\, F(s) &= det\{I + [(G_d(s) + G_m(s)]R(s)\} = \\ &= det[R^{-1}(s) + G_d(s) + G_m(s)]\, det\, R(s) = \\ &= det\, F_1(s)\, det\, R(s) \end{aligned} \quad (10)$$

where $F_1(s) = R^{-1}(s) + G_d(s) + G_m(s)$ (11)

In view of (11), *Theorem 2* reads as follows:

Corollary 1

A closed-loop comprising the system (9) and the decentralized controller (8) is stable if and only if

1. $det\, F_1(s) \neq 0 \quad \forall s \in D$
2. $N[0, det\, F_1(s)] + N[0, det\, R(s)] = n_q$ (12)

In $F_1(s)$ in (12), $[R^{-1}(s) + G_d(s)]$ is a diagonal matrix related to subsystems. Denote

$$R^{-1}(s) + G_d(s) = P(s) \quad (13)$$

where $P(s) = diag\{p_i(s)\}_{m \times m}$. From (13) results

$$I + R(s)[G_d(s) - P(s)] = 0 \quad (14)$$

For individual subsystems, (14) breaks down to

$$1 + R_i(s)G_i^{eq}(s) = 0 \qquad i = 1,2,...,m \quad (15)$$

where $G_i^{eq}(s) = G_i(s) - p_i(s) \quad i = 1,2,...,m$ (16)

is transfer function of the *i-th equivalent subsystem* (Kozáková and Veselý, 2003). Substituting (13) into (11) we obtain

$$det\, F_1(s) = det[P(s) + G_m(s)] \quad (17)$$

Using (17) it is possible to formulate stability conditions for the closed-loop system under a decentralized controller (Kozáková and Veselý, 2003; 2007).

Corollary 2 (Nominal stability under DC)

A closed-loop comprising the nominal system (9) and a decentralized controller (8) is stable if there exists a stable matrix $P(s) = diag\{p_i(s)\}_{m \times m}$ such that each equivalent subsystem (16) can be stabilized by its related local controller $R_i(s)$, i.e. each equivalent closed-loop characteristic polynomial

$$CLCP_i^{eq} = 1 + R_i(s)G_i^{eq}(s) \quad i = 1,2,...,m$$

has stable roots and the following conditions are met

1. $det[P(s) + G_m(s)] \neq 0$ (18)
2. $N\{0, det[P(s) + G_m(s)]\} = n_q$ (19)

Corollary 3 (Robust stability under DC)

The $M - \Delta$ structure is stable if there exists such $P(s) = diag\{p_i(s)\}_{m \times m}$ that conditions (18) and (19) are met and for either of the uncertainty forms (2), (3), (4) holds the corresponding inequality:

- *Additive uncertainty*

$$\sigma_M\{[P(j\omega) + G_m(j\omega)]^{-1}\} < \frac{1}{\ell_a(\omega)} \quad (20)$$

- *Multiplicative input uncertainty*

$$\sigma_M\{[P(j\omega) + G_m(j\omega)]^{-1} G_N(s)\} < \frac{1}{\ell_i(\omega)} \quad (21)$$

- *Multiplicative output uncertainty*

$$\sigma_M\{G_N(j\omega)[P(j\omega) + G_m(j\omega)]^{-1}\} < \frac{1}{\ell_o(\omega)} \quad (22)$$

Hence, the problem to be solved in the robust decentralized controller design reduces to finding an appropriate $P(s) = diag\{p_i(s)\}_{m \times m}$ that fulfils both Corollaries 2 and 3. Applying this approach allows to consider the full mean parameter value model as the nominal system.

Thus far, following methods of selecting *P(s)* have been proposed:

1. *Choosing P(s) = p(s)I with identical entries in the diagonal*. If $p(s) = -g_\ell(s - \alpha)$ where $g_\ell(s)$ can be any fixed of the *m* characteristic functions of $[-G_m(s)]$ and $\alpha \geq 0$ is the specified feasible degree of stability, it is possible to achieve the degree of stability α for the full closed-loop system (Kozáková and Veselý, 2003; 2007). Moreover, if $p(s) = -g_\ell(s - \alpha)$ satisfies the $M - \Delta$ stability conditions for systems under a decentralized controller (Kozáková and Veselý, 2005b) then both the specified nominal performance and robust stability are guaranteed. To stabilize equivalent subsystems any graphical SISO frequency domain design technique can be applied independently. (e.g. Bode plots, Neymark D-partition method).

Application and main results of this design approach are illustrated in *Example 1.*

2. *Choosing* $P(s) = diag\{p_i(s)\}_{i=1,...,m}$ *with different diagonal entries*. In (Veselý and Kozáková, 2005a) a heuristic method has been proposed to find coefficients of stable $p_i(s)$ such that

$structure[p_i(s)] = structure[G_i(s)],\ i = 1,...,m$.

For a decentralized fixed structure (PI, PID) controller a design procedure has been developed yielding improved damping of $G_i(s)$. General suggestions for choosing *P(s)* are given in (Kozáková and Veselý, 2006): for both $P^{-1}(s)$ and $G_m(s)$ stable, the necessary and sufficient closed-loop stability condition is $\sigma_M[G_m(s)] < \sigma_m[P(s)]$.

Moreover, to guarantee robust stability, conditions (20), (21) or (22) have to be met in all cases.

In this paper an innovative approach for generating $P(s)$ with different diagonal entries is proposed. Its underlying idea consists in generating *P(s)* using (13) and to guarantee fulfilment of conditions (18), (19), (20), (21) and (22) formulated in the Corollaries 2 a 3 by local controller detuning.
The resulting robust controller design procedure involves two main stages: the initial design and the possible redesign. Individual design steps are as follows:

- *Initial design*

1. Choice of nominal model $G_N(s) = G_d(s) + G_m(s)$, computation of and plotting uncertainty bounds $\ell_k, k = a,i,o$ according to (2), (3) or (4).
2. Design of local controllers $R_i(s),\ i = 1,\dots,\ m$ for isolated subsystems, composing the resulting diagonal controller in form (for $\delta = 1$)

$$R(s) = \begin{bmatrix} \frac{R_1(s)}{\delta_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \frac{R_m(s)}{\delta_m} \end{bmatrix}$$

3. Generating $P(s) = R^{-1}(s) + G_d(s)$ according to (13).
4. Verification of the nominal stability condition (18) and (19) (*Corollary 2*)
5. Verification of robust stability (RS) conditions (20), (21), (22).

   If any of the RS conditions is satisfied, the designed controller guarantees nominal stability and performance as well as closed-loop stability in the whole operating range of the plant specified by the N transfer functions matrices. The design procedure stops.

- *Redesign*

  If robust stability conditions fail to be satisfied, the design procedure is to be repeated either for relaxed nominal performance requirements or the original controller $R(s) = diag\{\frac{R_i(s)}{\delta_i}\}_{m\times m}$ is to be detuned using the detuning coefficients $\delta_i, i = 1,\dots,m$ so as to satisfy robust stability conditions in the tightest possible way.

According to the detuning procedure proposed in (Osuský and Veselý, 2007), that $\delta_k,\ k \in \{1,\dots,m\}$, is changed (usually increased) which contributes the most to the fulfillment of the RS condition. Selection of such $\delta_k,\ k \in \{1,\dots,m\}$ is carried out in m steps in such a way that in the *i-th* step $i \in \{1,\dots,m\}$ just one particular δ_i is increased while the other remain unchanged and the RS condition is verified. The finally selected and changed $\delta_k, k \in \{1,\dots,m\}$ is the one with the most significant contribution to the fulfillment of the RS condition. It specifies and is applied to the local controller to modify its parameters according to $\frac{R_k(s)}{\delta_k}$.

The design procedure is illustrated in *Example 2*.

4. EXAMPLES

Example 1
(*P(s) with identical entries in the diagonal*)
Power system stabilizers (PSS) are used to enhance power system damping. In (Kozáková, 2004), the DC design methodology proposed in (Kozáková and Veselý, 2003) has been applied to design PSS with the fixed structure transfer function

$$PSS_i(s) = \frac{k_i s}{T_i s + 1},\ \ i = 1,2$$

for two generating units of the Slovak Power System. The linearized mathematical model of the MIMO system has been obtained from experiments on the model of the Slovak Power System.

$$G(s) = \begin{pmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{pmatrix}$$

where

$$G_{11}(s) = \frac{-4.4s^3 + 147.9s^2 + 731.7s - 2243}{s^4 + 8.3s^3 + 162.8s^2 + 509.5s + 5283}$$

$$G_{12}(s) = \frac{0.1278s^3 - 1.964s^2 + 15.21s - 28.61}{s^4 + 13.24s^3 + 65.76s^2 + 661.5s + 3.257}$$

$$G_{21}(s) = \frac{0.0097s^3 - 5.883s^2 + 18.77s - 165.8}{s^4 + 27.5s^3 + 52s^2 + 1191s + 5.4}$$

$$G_{22}(s) = \frac{-1.102s^3 + 134.7s^2 + 51.61s - 383.5}{s^4 + 7.599s^3 + 58.94s^2 + 335.6s + 58.04}$$

The PSS have been designed to reduce by 8.5dB the resonance peaks of equivalent subsystems. Local PSS´s for individual units have been designed using Bode plots of equivalent subsystems generated by $p_1(s)$. Using the standard design approach, parameters for both PSS have been chosen as follows

$$PSS_i(s) = \frac{0.0562s}{0.1s + 1} \quad i = 1,2$$

Bode plots of compensated equivalent subsystems depicted in Fig. 2 with thick lines prove the required resonance peak reduction. Experimental studies on a physical model of the Slovak Power System have proved effectiveness of the designed PSS´s in improving the power system damping in the required frequency range. One illustrative result – response of the active power deviation in both generating units with implemented PSS to a three phase to ground fault during 0.2s at the middle of the transmission line between both units is shown in Fig. 3b

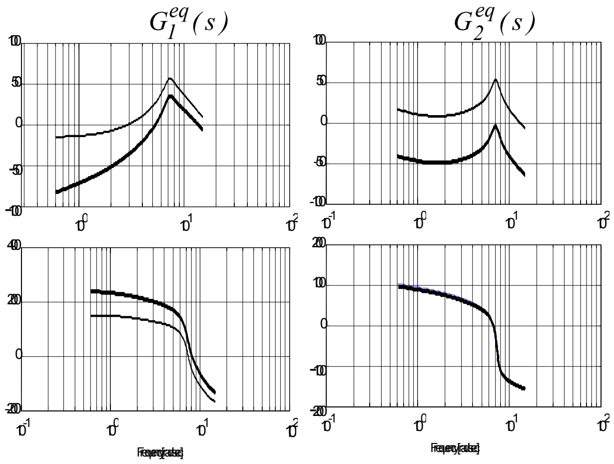

Fig. 2. Bode plots of equivalent subsystems $G_1^{eq}(s)$ and $G_2^{eq}(s)$ (thin lines – uncompensated subsystems; thick lines – subsystems with PSS compensation)

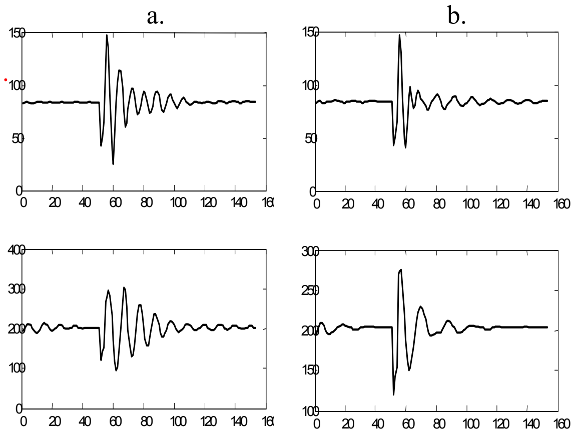

Fig. 3 Time responses of the active power deviation in Unit 1 (upper plots) and Unit 2 (lower plots) to a three phase to ground fault during 0.2s: a. uncompensated subsystems; b. subsystems with PSS compensation.

Example 2
(P(s) with different diagonal entries)

Consider the 3x3 transfer function model for a pilot scale binary distillation column used to separate ethanol and water (Hovd and Skogestad, 1994; Ogunnaike and Ray, 1994). A strong one-way interaction is evident from the large off-diagonal elements in the 3rd row.

$$G(s)=\begin{pmatrix} \frac{0.66e^{-2.6s}}{6.7s+1} & \frac{-0.61e^{-3.5s}}{8.64s+1} & \frac{-0.0049e^{-s}}{9.06s+1} \\ \frac{1.11e^{-6.5s}}{3.25s+1} & \frac{-2.36e^{-3s}}{5s+1} & \frac{-0.012e^{-1.2s}}{7.09s+1} \\ \frac{-33.68e^{-9.2s}}{8.15s+1} & \frac{46.2e^{-9.4s}}{10.9s+1} & \frac{0.87(11.61s+1)e^{-s}}{(3.89s+1)(18.8s+1)} \end{pmatrix}$$

Based on the RGA matrix

$$\Lambda=\begin{pmatrix} 1.95 & -0.65 & -0.3 \\ -0.66 & 1.88 & -0.22 \\ -0.29 & -0.23 & 1.52 \end{pmatrix}$$

the full system has been partitioned into the diagonal part (subsystems) and interactions (9). A low value of Niederlinski index ($N = 0.3752$) and a high value of the VA index - sufficient condition for correct input-output pairing (Kozáková, 1998), VA = 54.679 (instead of preferred VA<1) indicate difficulties in structural controllability of the plant.

For the design purpose, time delays have been replaced with the 6th order Padé approximants. Uncertainty bounds (2), (3) and (4) have been computed for $\pm 15\%$ changes in parameter values of all entries of $G(s)=G_N(s)$.

PID controller transfer functions for decoupled subsystems have been chosen

$$R_i(s)=\frac{r_d s^2+r_0 s+r_{-1}}{ks},\ i=1,2,\dots,m$$

where k is the common factor applied simultaneously in all loops in the redesign step to fulfil the robust stability conditions (20), (21), (22).

The $\left|\frac{1}{\ell_k(\omega)}\right|$, $k=a,i,o$ plots are depicted in Fig. 4, local controllers have been designed for the worst case – i.e. the multiplicative output uncertainty.

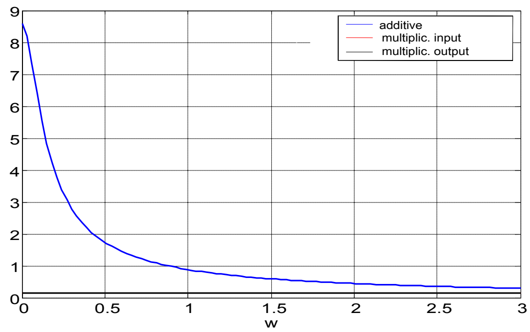

Fig. 4 The $\left|\frac{1}{\ell_k(\omega)}\right|$ - versus - ω plots for $k=a,i,o$

Final values of local controller parameters have been chosen as follows

$$R_1(s)=\frac{0.0637s^2+0.3186s+0.0574}{s}$$

$$R_2(s)=\frac{-(0.1593s^2+0.1912s+0.0478)}{s}$$

$$R_3(s)=\frac{0.1593s^2+2.5490s+0.7966}{s}$$

Fig. 5 shows that with the chosen decentralized controller, the robust stability conditions are verified.

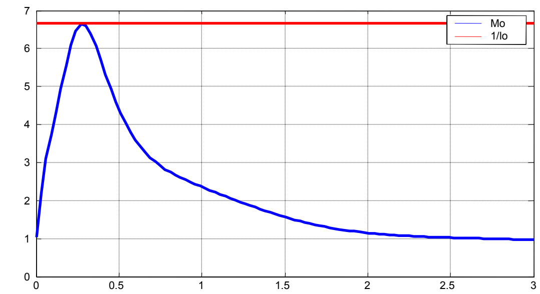

Fig. 5 Verification of the robust stability condition under the designed DC and multiplicative output uncertainty: $\sigma_M [M_0(s)] < \dfrac{1}{|\ell_0|}$

Closed-loop step responses of the nominal system for the reference signal $[1\ 0\ 0]^T$ are in Fig. 6, Fig. 7 shows simulation results for unit steps applied in all subsystems at different step times (12s, 5s, 20s for the 1st, 2nd and 3rd subsystem, respectively).

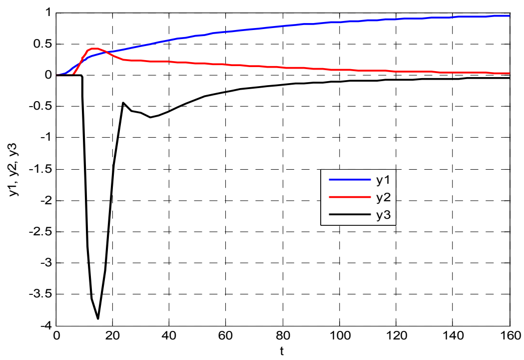

Fig. 6 Closed-loop step responses under the designed DC for the reference unit step in the first subsystem

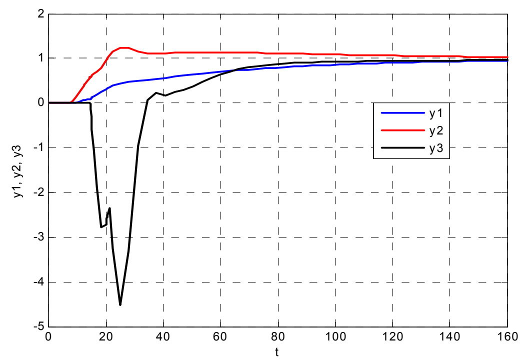

Fig. 7 Closed-loop step responses under the designed DC for the reference unit steps applied in all subsystems at different step times (12s, 5s, 20s)

5. CONCLUSION

In this paper an improvement to the existing robust decentralized controller design technique for continuous-time uncertain systems has been proposed. Applying the generalized Nyquist stability criterion and the M-Δ structure robust stability conditions adapted for the decentralized control structure, the problem to be solved in the robust decentralized controller design reduces to finding an appropriate $P(s) = diag\{ p_i(s) \}_{m \times m}$ guaranteeing both nominal and robust closed-loop stability of the full system under a decentralized controller. Moreover, this approach allows considering the full mean parameter value model as the nominal system. An innovation in choosing $P(s)$ with different diagonal entries has been proposed, resulting in a simple-to-use insightful graphical design procedure that involves two main stages: in the initial design stage, local controllers are designed for isolated subsystems, the matrix *P(s)* is generated and the nominal and robust stability conditions are verified. If they fail to be satisfied, in the redesign stage, the local controllers transfer functions are modified so as to satisfy robust stability conditions in the tightest possible way.

The proposed practice-oriented approach has been applied in the design of robust decentralized PID controllers for real plant models (a 2x2 power system with two generating units and a 3x3 laboratory binary distillation column) show practical applicability of the proposed design philosophy.

ACKNOWLEDGEMENT

This work has been supported by the Slovak Grant Agency under Grant. No. 1/0544/09.

REFERENCES

Hovd, M. and S. Skogestad (1994). Sequential design of decentralized controllers. *Automatica,* 30, 1601-1607.

Kozáková, A. (1998). Robust decentralized control of complex systems in the frequency domain. In: *2nd IFAC Workshop New Trends in Design of Control Systems,* Elsevier, Kidlington, UK.

Kozáková, A. (2004). PSS design for a multivariable system in the frequency domain. In *6th Int. Conference Control of Power System*, Štrbské Pleso, Slovak Republic.

Kozáková, A. and V. Veselý (2003). Independent design of decentralized controllers for specified closed-loop performance. In: *European Control Conference ECC'03*, Cambridge, UK

Kozáková, A. and V. Veselý (2005). A frequency domain design technique for robust decentralized controllers. In *16th IFAC World Congress,* Prague, Czech Republic.

Kozáková, A. and V. Veselý (2006). Robust decentralized controller design: independent design. In *IFAC Workshop ALSIS'06,* Helsinki, Finland.

Kozáková, A., Veselý, V. (2007). Independent design of decentralized controllers in the frequency domain. *Periodica Polytechnica Electrical Engineering*, 51/1-2, 1-9. ISSN 0324-6000.

MacFarlane, A.G.J. and I.Postlethwaite (1977). The generalized Nyquist stability criterion and multivariable root loci. *Int. J. Control,* **25**, 81-127.

Ogunnaike, B.A. and W.H. Ray (1994). *Process dynamics, modelling and control*. Oxford University Press, New York – Oxford.

Osuský, J. and V. Veselý (2007). Robust Decentralized Controller Design in Frequency Domain. In: *16th Int. Conference Process Control 2007*. Štrbské Pleso, Slovak Republic.

Skogestad, S. and M. Morari (1989). Robust performance of decentralized control systems by independent designs. *Automatica*, **25**, 119-125.

Skogestad, S. and I. Postlethwaite (1996). *Multivariable fedback control: analysis and design*. (3rd edn.) John Wiley & Sons Ltd., Chichester New York Brisbane Toronto Singapore.

Veselý, V. and A. Kozáková (2005a). Independent design of robust decentralized controllers. *In 1st Int. Workshop Advanced Control Circuits and Systems (ACCS´05)*, Cairo, Egypt.

Veselý, V. and Kozáková, A. (2005b). A power system application of a robust decentralized controller design methodology. *Archives of Control Sciences,* 15, No. 2, 137-148. ISSN 000