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Predictive controllers integrated with economic optimization tolerating actuator faults: application to a nonlinear plant

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Plan of presentation

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   2.2. Economic optimization problem
   2.3. Predictive algorithms integrated with economic optimization
3. Actuator faults handling
4. Example control system
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Introduction

- *Algorithms*: Model Predictive Control algorithms integrated with Economic Optimization (MPCEO)
- *Aim*: Continuation of the control system operation till the failure is fixed
- *Assumption*: Methods of detection and isolation of actuator faults are available, measurement of the actuator output, in particular
- *Remark*: Output constraints are often important for safety and economic effectiveness of the process

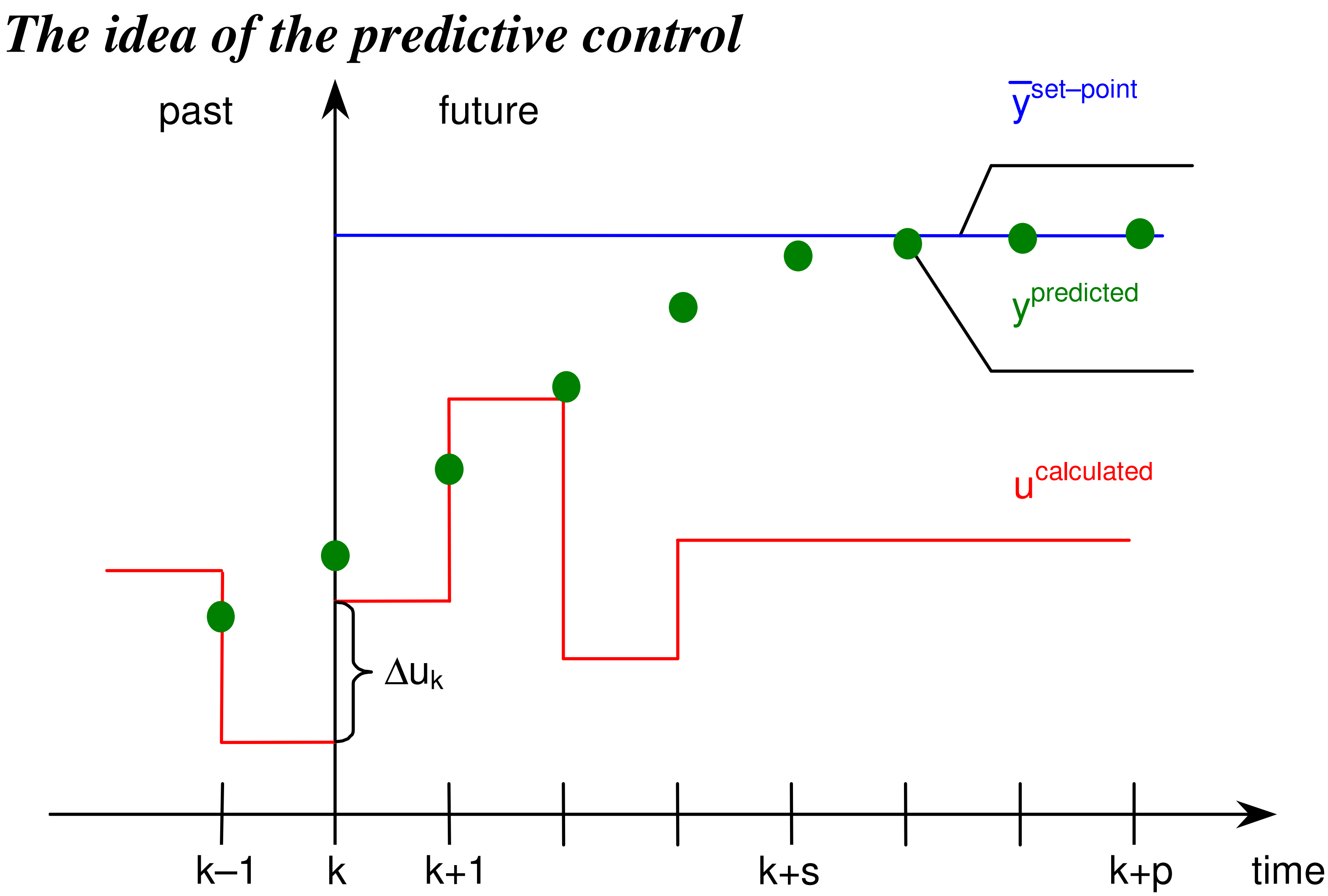

Fig. 1. Idea of predictive control; p – prediction horizon, s – control horizon, Δu_k – control signal change at current iteration

Numerical predictive control algorithms

Following problem is solved at each iteration:

$$\min_{\boldsymbol{\Delta u}} \left\{ J_{MPC} = \sum_{j=1}^{n_y} \sum_{i=1}^{p} \kappa_j \cdot \left(\overline{y}_k^j - y_{k+i|k}^j \right)^2 + \sum_{j=1}^{n_u} \sum_{i=0}^{s-1} \lambda_j \cdot \left(\Delta u_{k+i|k}^j \right)^2 \right\}$$

subject to the constraints:

$$\boldsymbol{\Delta u}_{min} \le \boldsymbol{\Delta u} \le \boldsymbol{\Delta u}_{max},$$

$$\boldsymbol{u}_{min} \le \boldsymbol{u} \le \boldsymbol{u}_{max},$$

$$\boldsymbol{y}_{min} \le \boldsymbol{y} \le \boldsymbol{y}_{max},$$

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subject to the constraints:

$$\boldsymbol{\Delta u}_{min} \le \boldsymbol{\Delta u} \le \boldsymbol{\Delta u}_{max},\ \boldsymbol{u}_{min} \le \boldsymbol{u} \le \boldsymbol{u}_{max},\ \boldsymbol{y}_{min} \le \boldsymbol{y} \le \boldsymbol{y}_{max},$$

- In a nonlinear case, in order to avoid problems connected with general nonlinear optimization, effective algorithms with model linearization and quadratic optimization are used
- A few such algorithms are available, so the algorithm most suitable for a given nonlinear plant can be selected and a compromise between control performance and computation demand can be achieved

Economic optimization problem

$$\min_{\bar{\boldsymbol{y}}} J_E(\bar{\boldsymbol{y}}, \bar{\boldsymbol{u}})$$

subject to

$$\bar{\boldsymbol{u}}_{\min} \le \bar{\boldsymbol{u}} \le \bar{\boldsymbol{u}}_{\max}$$

$$\bar{\boldsymbol{y}}_{\min} + \bar{\boldsymbol{r}}_{\min} \le \bar{\boldsymbol{y}} \le \bar{\boldsymbol{y}}_{\max} - \bar{\boldsymbol{r}}_{\max}$$

$$\bar{\boldsymbol{y}} = F(\bar{\boldsymbol{u}}, \tilde{\boldsymbol{w}})$$

$F : \Re^{n_u} \times \Re^{n_w} \rightarrow \Re^{n_y}$ is a steady–state plant model (u – inputs, y – outputs, w – disturbances)

- Precise nonlinear steady–state plant model

Classical multilayer control system structure

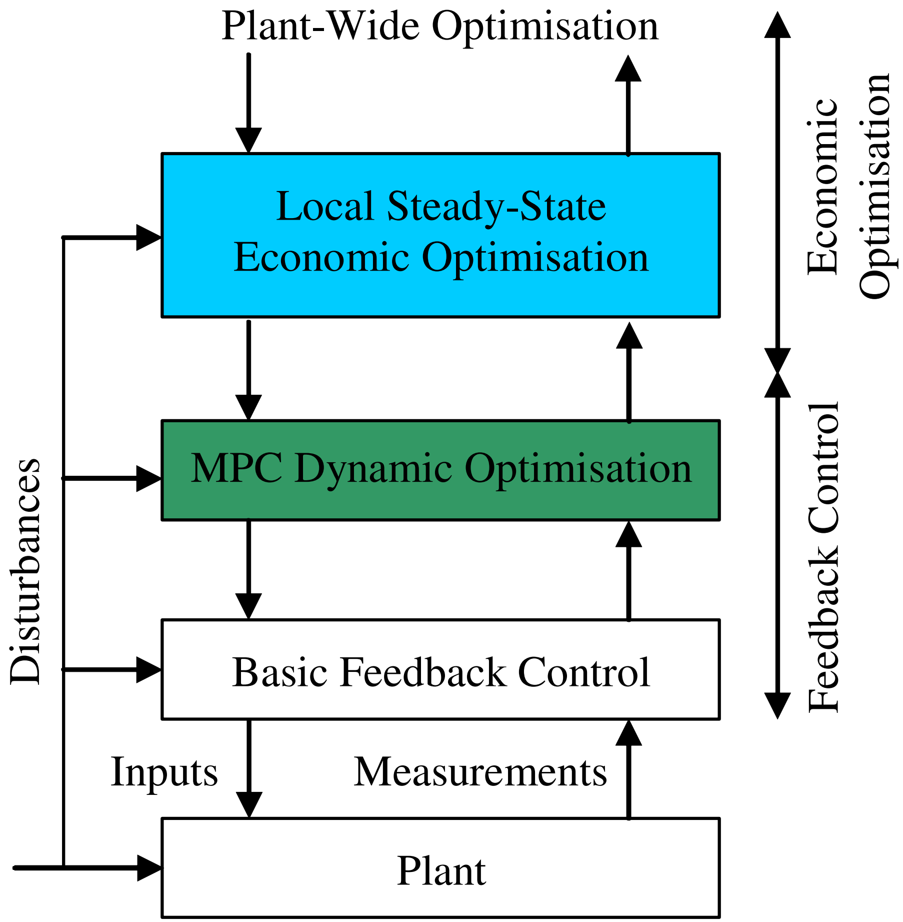


Fig. 2. Hierarchical control system structure with MPC advanced control layer

MPC Integrated with Economic Optimization (MPCEO)

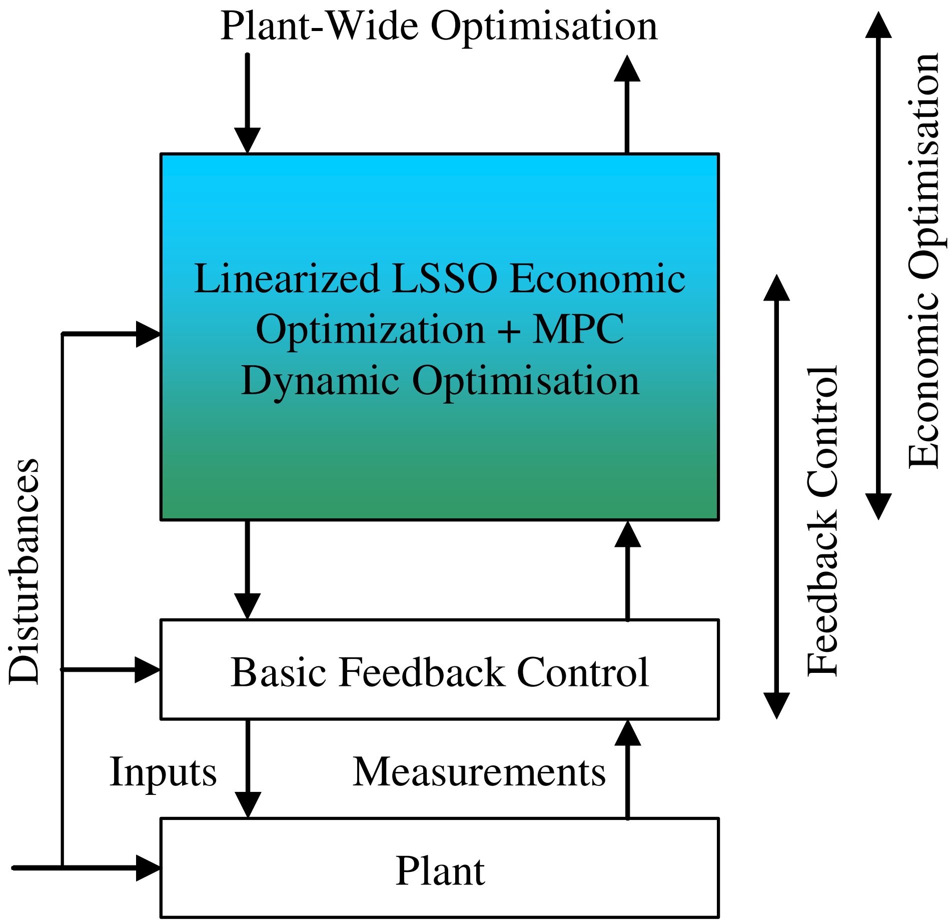


Fig. 3. Control system structure with MPC integrated with economic optimisation

MPC Integrated with Economic Optimization (MPCEO)

- One of the methods to cope with disturbances changing quickly comparing to the dynamics of the control plant
- The steady–state control plant model is linearized
- Only one quadratic optimization problem must be solved at each iteration
- The control system structure is simplified
- The economic optimization is performed more often than in the classic hierarchical approach

MPC Integrated with Economic Optimization (MPCEO)

$$\min_{\Delta u, \bar{y}} J_{MPC}(\bar{\boldsymbol{y}}, \Delta \boldsymbol{u}) + \gamma \cdot J_E(\bar{\boldsymbol{y}}, \bar{\boldsymbol{u}})$$

subject to

$$\Delta \boldsymbol{u}_{min} \leq \Delta \boldsymbol{u} \leq \Delta \boldsymbol{u}_{max},$$

$$\boldsymbol{u}_{min} \leq \boldsymbol{u} \leq \boldsymbol{u}_{max},$$

$$\boldsymbol{y}_{min} \leq \boldsymbol{y} \leq \boldsymbol{y}_{max},$$

$$\bar{\boldsymbol{u}}_{\min} \leq \bar{\boldsymbol{u}} \leq \bar{\boldsymbol{u}}_{\max}$$

$$\bar{\boldsymbol{y}}_{\min} + \bar{\boldsymbol{r}}_{\min} \leq \bar{\boldsymbol{y}} \leq \bar{\boldsymbol{y}}_{\max} - \bar{\boldsymbol{r}}_{\max}$$

$$\bar{y} = F\left(\boldsymbol{u}(k-1), \tilde{w}\right) + \boldsymbol{H}(k)\left(\bar{\boldsymbol{u}} - \boldsymbol{u}(k-1)\right)$$

constraints from economic optimization problem

economic optimization performance function

linearization of the steady-state nonlinear model *F*

Actuator faults handling

- A set of equality constraints is added to the algorithm after fault detection

$$\Delta u^{m}_{k+i|k} = 0, i = 0, \ldots, s-1$$

m – number of control signal affected by the failure

- Application is relatively easy
- Elimination of some decision variables

Actuator faults handling

- Equality constraint is added

$$\bar{u}^m = u_{bl}^m$$

m – number of control signal affected by the failure
u_{bl}^m – output of the actuator

- Easy application
- The steady–state model is in practice modified
- Measurement of the actuator output is often available

Control plant (evaporator system)*

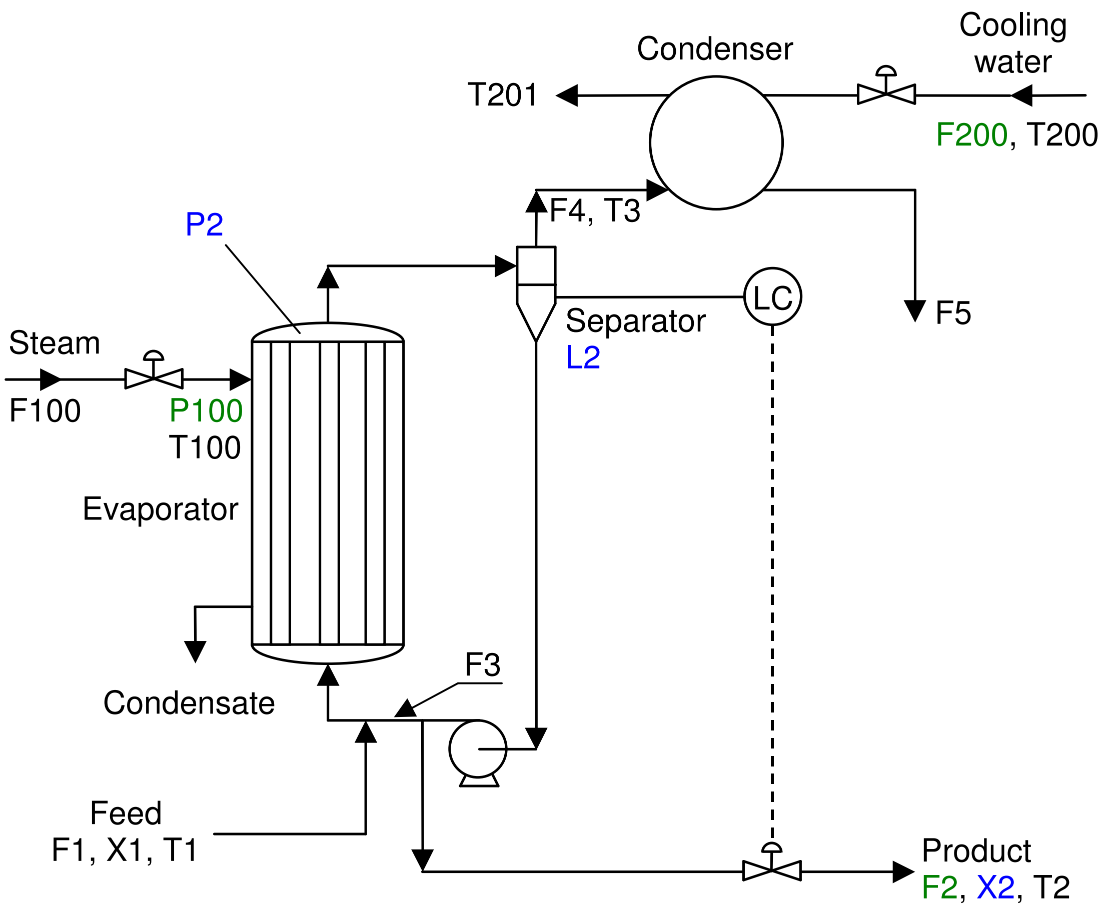


Fig. 4. Evaporator system

Output Variables
$L2$ – separator level,
$X2$ – product composition,
$P2$ – operating pressure

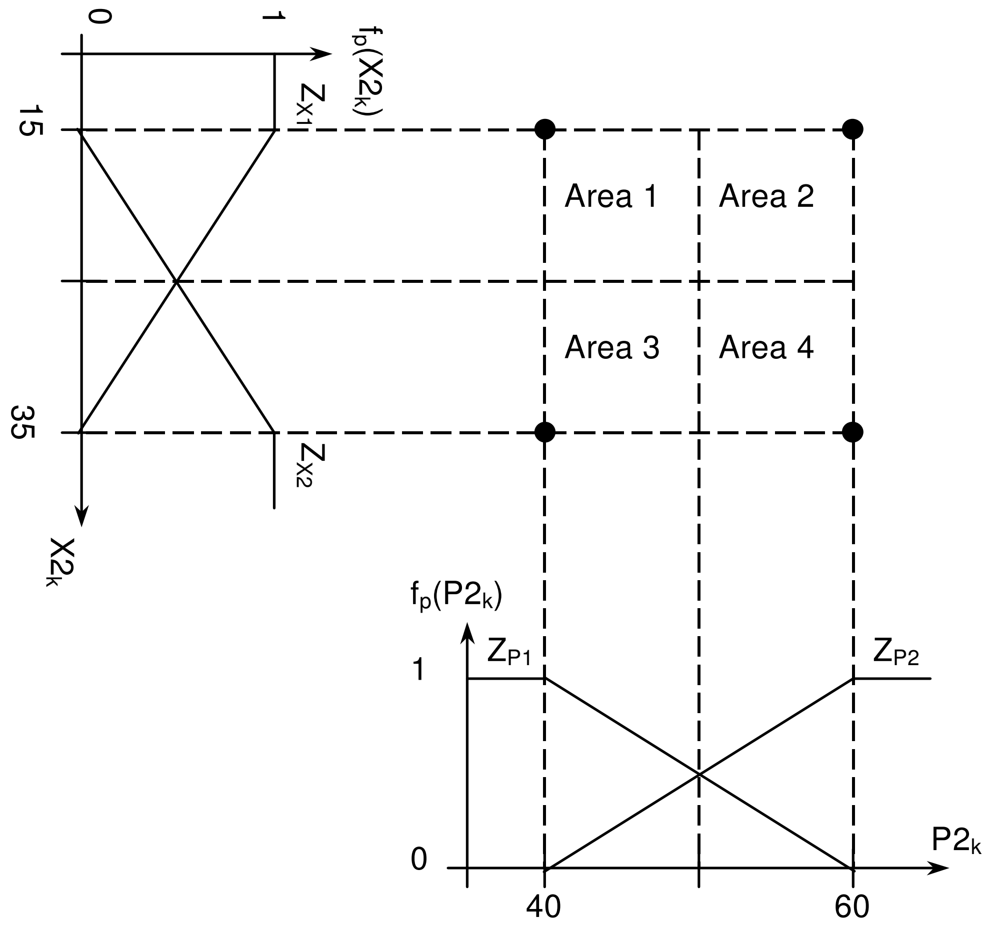
Manipulated variables
$F2$ – product flowrate,
$P100$ – steam pressure,
$F200$ – cooling water flowrate

* R.B. Newell, P.L. Lee: *Applied process control – a case study*; Prentice Hall, 1989

The MPCEO algorithm

- The manipulated variables are: steam pressure $P100$ and cooling water flow $F200$
- The controlled variables are: product composition $X2$ and pressure in the evaporator $P2$
- Measured disturbance $F1$ (feed flow)
- Based on the fuzzy DMC predictive algorithm,

The MPCEO algorithm



Parameters:

$\kappa_{P2}=\kappa_{X2}=1$,
$\lambda_{P100}= \lambda_{F200}=\lambda_{F3}=0.1$
p=100, s=10

Fig. 5. Membership functions of the fuzzy MPCEO controller

The MPCEO algorithm

- Economic performance index (cost of production)

$$J_E = c_1 \cdot \overline{P}100 - c_2 \cdot \overline{F}2$$

- Constraints put on manipulated variables:

$$0 \text{ kPa} \le P100 \le 400 \text{ kPa}, \ 0 \text{ kg/min} \le F200 \le 400 \text{ kg/min},$$

- The product should fulfill purity criteria:

$$25\ \% \le X2$$

- The appropriate soft constraints were put on the predicted $X2$ composition values

- The constraint put on $\overline{X}2$ set–point was as follows

$$\overline{X}2_{\min} + \overline{r}_{\min}^{X2} \le \overline{X}2$$

$$\overline{X}2_{\min} = X2_{\min} = 25\%, \quad \overline{r}_{\min}^{X2} = 1\%$$

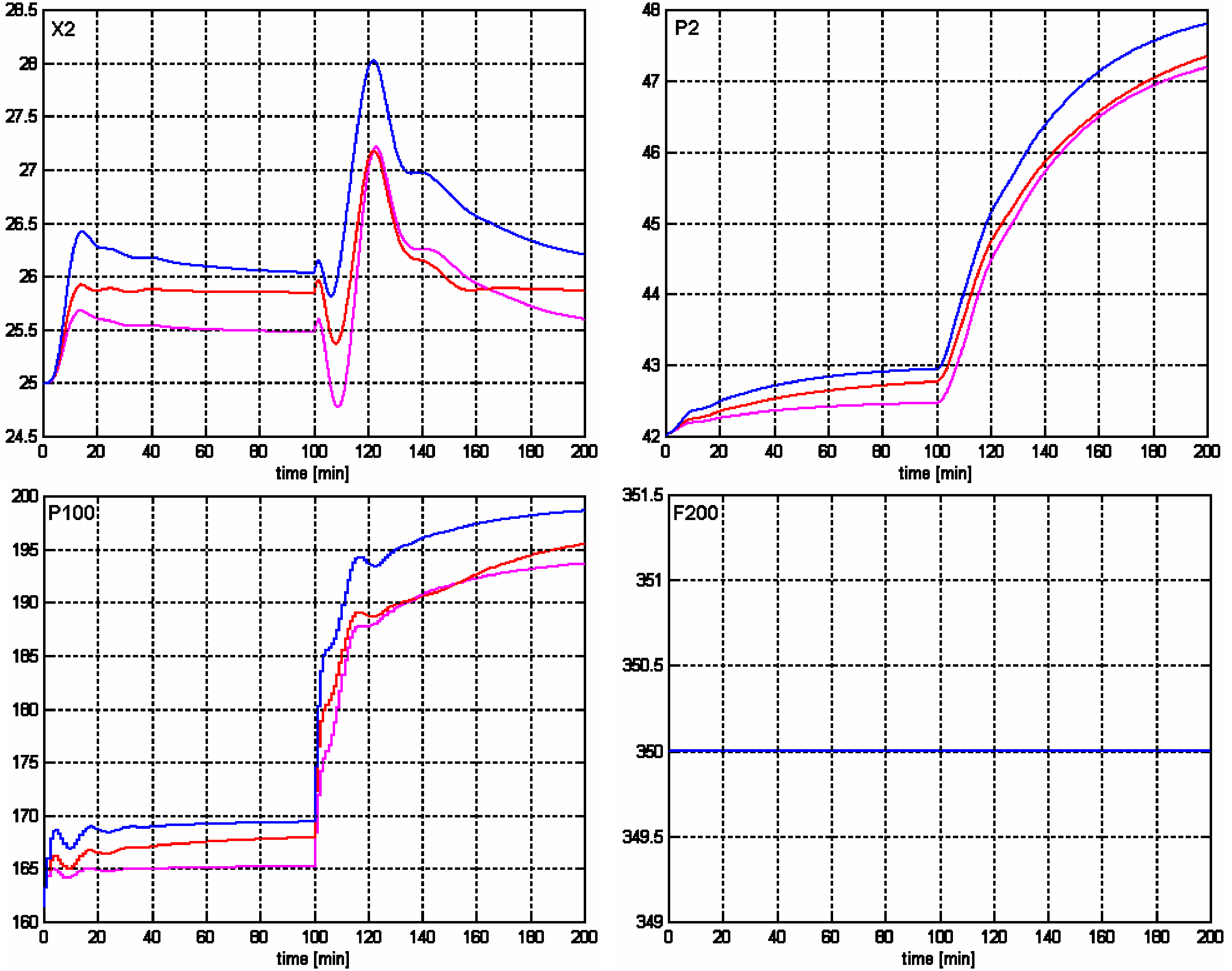


Fig. 6. Responses of the control system to a step decrease of *F*1 disturbance in the 100th minute; *F*200 actuator fault: not taken into consideration at all, taken into consideration, additionally the equality constraint put on *X*2 set-point was added; above: output signals *X*2 and *P*2, below: control signals *P*100 and *F*200

*P*100 *actuator blockade*

- Optimizing procedure returned the message that there is no admissible solution
- Why there is no solution found?
- In order to answer this question steady–state characteristics should be analyzed

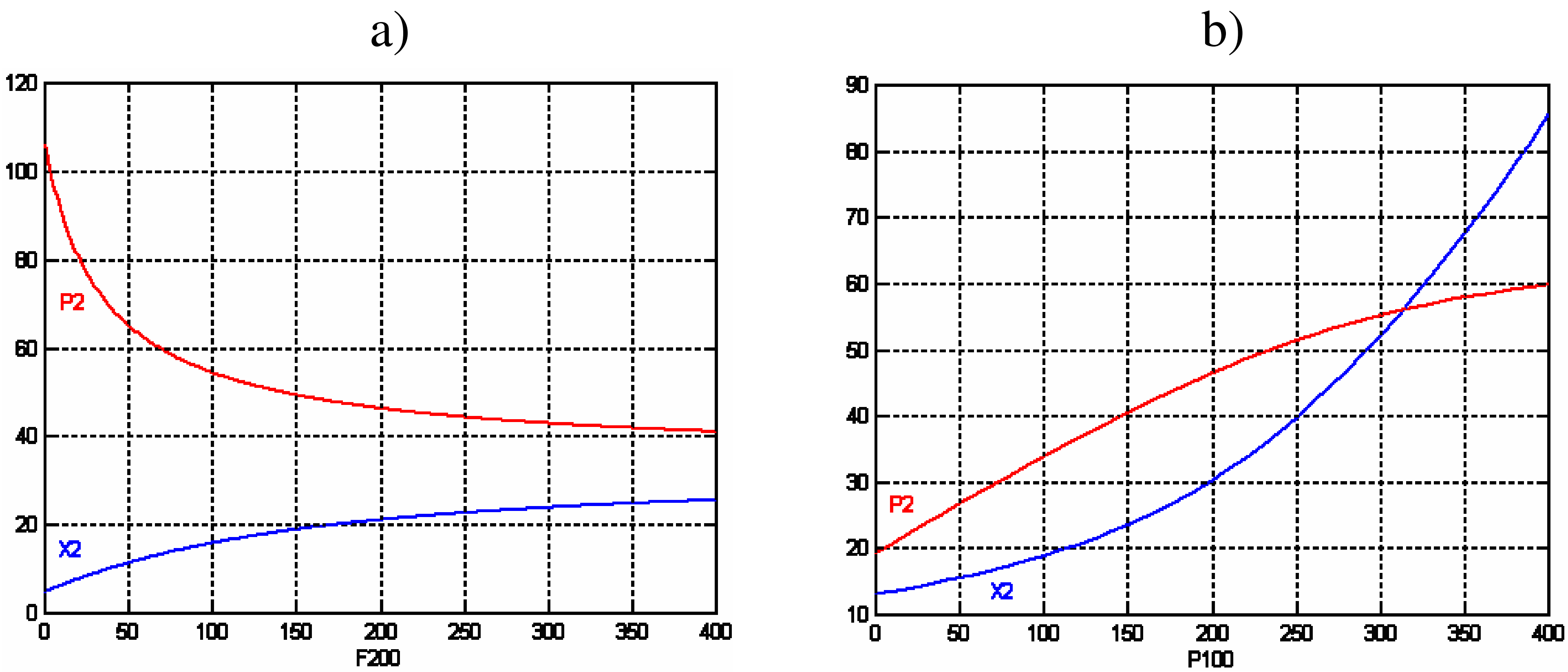


Fig. 7. Steady–state characteristics a) X2(F200) i P2(F200), b) X2(P100) i P2(P100), of the plant with blocked actuator of the manipulated variable a) *P*100, b) *F*200

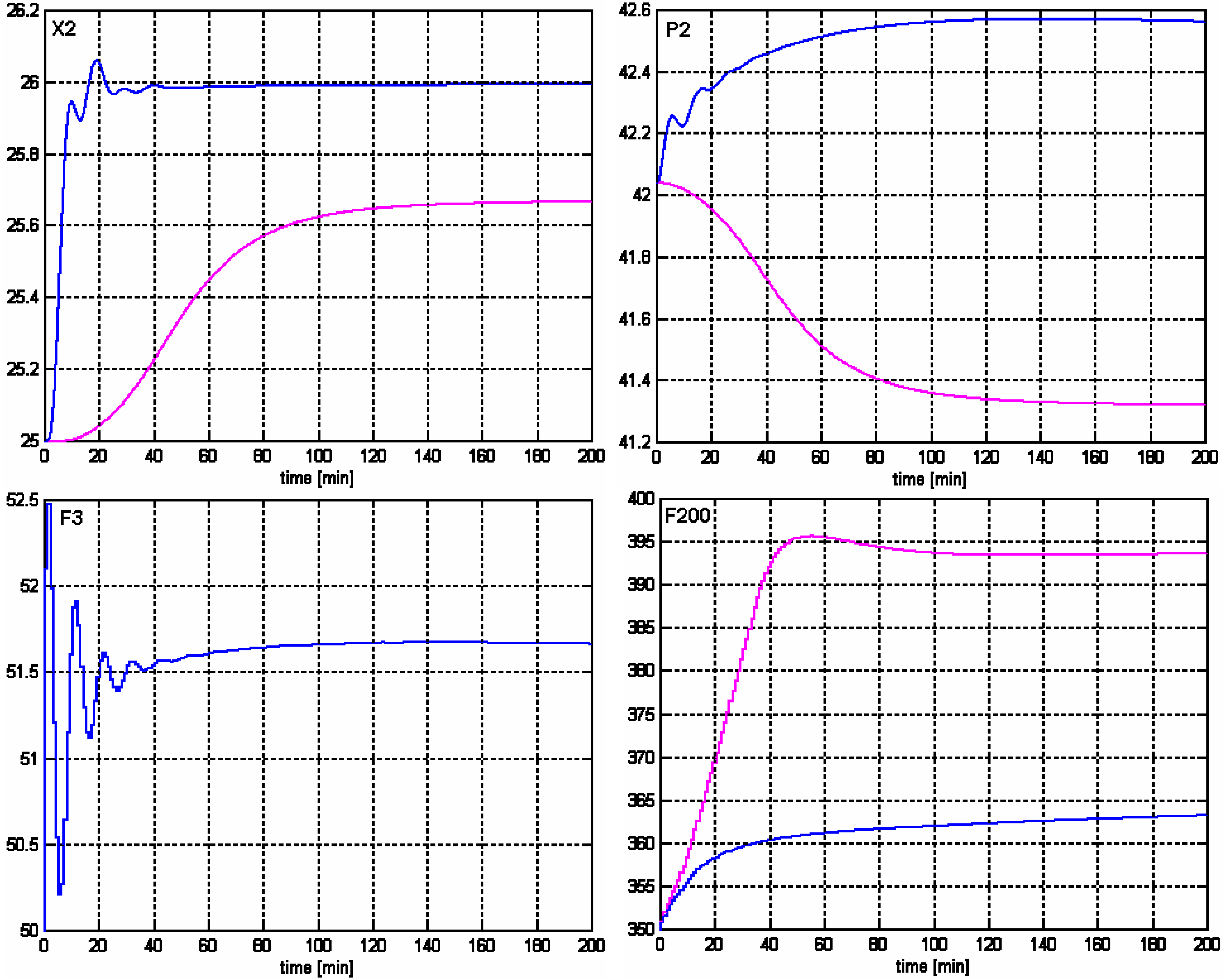


Fig. 8. Responses of the control system obtained for blockade of the $P100$ actuator: not taken into consideration, taken into consideration in the control system with additional manipulated variable above: output signals $X2$ and $P2$, below: control signals $F3$ and $F200$

Summary

- Effective and relatively little complicated method of actuator fault toleration in control systems with MPCEO algorithms and output constraints
- The method: equality constraints added to the optimization problem solved by the algorithm
- The method can be used in the MPCEO algorithm with either linear or nonlinear dynamic control plant model
- Further improvement of control system operation can be obtained, when the additional manipulated variable is available