AN ALTERNATIVE CONTROL FOR PROCESS IN FAULT CONDITIONS

Eugen Iancu, Matei Vînătoru

Automation and Mechatronics Department
University of Craiova
E-mail: Eugen.Iancu@automation.ucv.ro, vinatoru@automation.ucv.ro

Abstract: In this paper, the authors propose some practical behaviour in control and supervising of complex process (MIMO), in presence of actuators faults. The fault detection and isolation (FDI) problem is an inherently complex one. Because of this reason, we have considered the case when one or more actuators are blocking in a fixed position or are not supplied (in this case the servomechanism are in the total closed or total open position). The immediate goals is to preserve the stability of process and, if is possible, to control the process in a slightly degraded manner.

Key words: Control systems, fault detection and isolation, superheater control.

CONTROL SYSTEM SYNTHESIS IN FAULT FREE CONDITIONS

In most cases, industrial processes have multiple inputs and outputs. For these situations, are known methods for analyse and synthesis of control systems. We consider the structure represented in figure 1. The significance's of the used notations are the followings:

- $C_1 \ldots C_n$ - controllers
- D.U. - device for uncoupling of outputs
- $A_1 \ldots A_n$ - actuators
- $v_1 \ldots v_n$ - references inputs
- $y_1 \ldots y_n$ - outputs of process
- $r_1 \ldots r_n$ - outputs generates by the controllers
- $c_1 \ldots c_n$ - outputs of D.U. block
- $u_1 \ldots u_n$ - real inputs of the process

To illustrate the classical algorithm used for synthesis of D.U., consider the next example. Let be the transfer matrix attached to the process:

$$H_p(s) = \begin{bmatrix} H_{p11}(s) & H_{p12}(s) \\ H_{p21}(s) & H_{p22}(s) \end{bmatrix} \tag{1}$$

and the transfer function for actuators, who are considered proportionally, for simplify the calculus:

$$K_A = \begin{bmatrix} k_{a1} & 0 \\ 0 & k_{a2} \end{bmatrix} \tag{2}$$

The transfer matrix for uncoupling device is:

$$D(s) = \begin{bmatrix} D_{11}(s) & D_{12}(s) \\ D_{21}(s) & D_{22}(s) \end{bmatrix} \tag{3}$$

where:

$$D_{ij}(s) = \left. \frac{C_i(s)}{R_j(s)} \right|_{R_k(s)\equiv 0, \forall k \neq j, i=\overline{1,2}, j=\overline{1,2}, k=\overline{1,2}.} \tag{4}$$

To obtain a faster response of the system, we can choose $D(s)$ with the form:

$$D(s) = \begin{bmatrix} 1 & D_{12}(s) \\ D_{21}(s) & 1 \end{bmatrix} \tag{5}$$

For carry out the uncoupling, it is necessary that the transfer matrix:

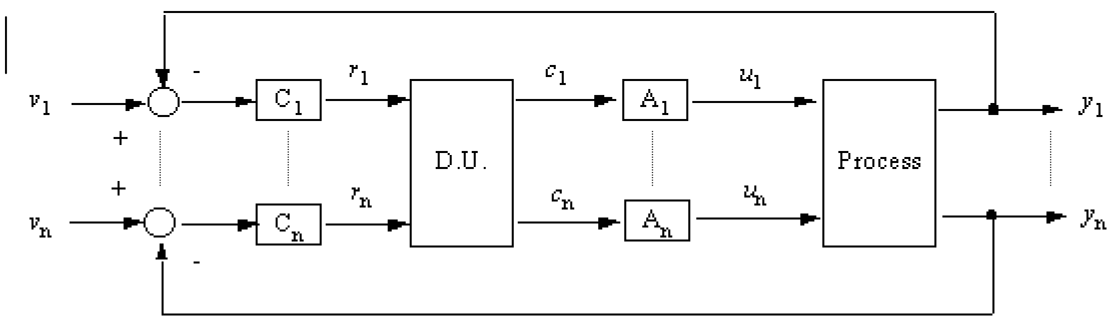

Fig. 1.

$$G(s) = H_p(s) K_A D(s) \quad (6)$$

to has the form:

$$G(s) = \begin{bmatrix} G_{11}(s) & 0 \\ 0 & G_{22}(s) \end{bmatrix} \quad (7)$$

So, we have:

$$k_{a1} H_{p11}(s) D_{12}(s) + k_{a2} H_{p12}(s) = 0$$
$$\Rightarrow D_{12}(s) = -\frac{k_{a2} H_{p12}(s)}{k_{a1} H_{p11}(s)} \quad (8)$$

$$k_{a2} H_{p22}(s) D_{21}(s) + k_{a1} H_{p21}(s) = 0$$
$$\Rightarrow D_{21}(s) = -\frac{k_{a1} H_{p21}(s)}{k_{a2} H_{p22}(s)} \quad (9)$$

and respectively:

$$G_{11}(s) = k_{a1} \left[H_{p11}(s) - \frac{H_{p12}(s) H_{p21}(s)}{H_{p22}(s)} \right] \quad (10)$$

$$G_{22}(s) = k_{a2} \left[H_{p22}(s) - \frac{H_{p12}(s) H_{p21}(s)}{H_{p11}(s)} \right] \quad (11)$$

Another suggestion of the authors, if it is possible, is to impose the $G(s)$ matrix with the form:

$$G(s) = \begin{bmatrix} H_{p11}(s) & 0 \\ 0 & H_{p22}(s) \end{bmatrix} \quad (12)$$

In this case we respect the dynamic input-output of the process on the principals channels. In these conditions, for $D(s)$ with generally form (3), we have the relations:

$$k_{a1} H_{p11}(s) D_{11}(s) + k_{a2} H_{p12}(s) D_{21}(s) = \\ = H_{p11}(s) = G_{11}(s) \quad (13)$$

$$k_{a1} H_{p11}(s) D_{12}(s) + k_{a2} H_{p12}(s) D_{22}(s) = 0 \quad (14)$$

$$k_{a1} H_{p21}(s) D_{11}(s) + k_{a2} H_{p22}(s) D_{21}(s) = 0 \quad (15)$$

$$k_{a1} H_{p21}(s) D_{12}(s) + k_{a2} H_{p22}(s) D_{22}(s) = \\ = H_{p22}(s) = G_{22}(s) \quad (16)$$

From (13), (14), (15) and (16) we obtain the expression of the components of $D(s)$ matrix:

$$D_{11}(s) = \frac{H_{p11}(s) H_{p22}(s)}{k_{a1}[H_{p11}(s) H_{p22}(s) - H_{p12}(s) H_{p21}(s)]} \quad (17)$$

$$D_{12}(s) = \frac{-H_{p12}(s) H_{p22}(s)}{k_{a1}[H_{p11}(s) H_{p22}(s) - H_{p12}(s) H_{p21}(s)]} \quad (18)$$

$$D_{21}(s) = \frac{-H_{p11}(s) H_{p21}(s)}{k_{a2}[H_{p11}(s) H_{p22}(s) - H_{p12}(s) H_{p21}(s)]} \quad (19)$$

$$D_{22}(s) = \frac{-H_{p11}(s) H_{p22}(s)}{k_{a2}[H_{p11}(s) H_{p22}(s) - H_{p12}(s) H_{p21}(s)]} \quad (20)$$

If we consider also the transfer matrix attached to the controllers:

$$C(s) = \begin{bmatrix} C_1(s) & 0 \\ 0 & C_2(s) \end{bmatrix} \quad (21)$$

the transfer matrix for the structure represented in fig. 1 is:

$$S(s) = \begin{bmatrix} \frac{G_{11}(s) C_1(s)}{1 + G_{11}(s) C_1(s)} & 0 \\ 0 & \frac{G_{22}(s) C_2(s)}{1 + G_{22}(s) C_2(s)} \end{bmatrix} \quad (22)$$

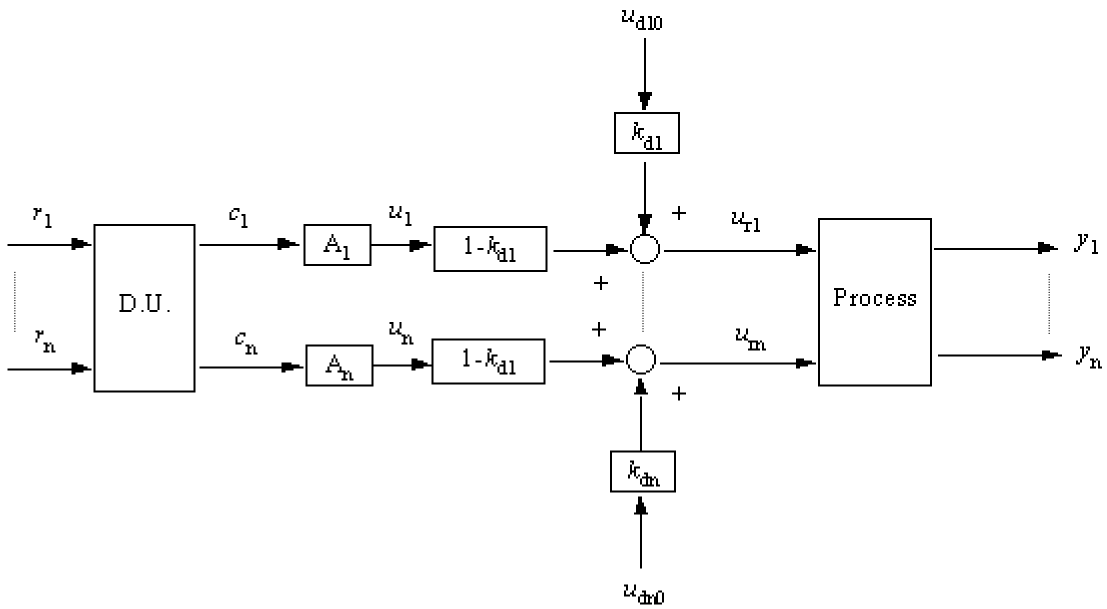

Fig. 2.

If

$$S(s) \equiv S^{*}(s) \tag{23}$$

we obtain for the controllers the next expressions:

$$C_i(s) = \frac{S_{ii}^{*}(s)}{1 - S_{ii}^{*}(s)} \frac{1}{G_{ii}(s)}, i = \overline{1,2}. \tag{24}$$

CONTROL SYSTEM SYNTHESIS IN FAULT CONDITIONS

We suppose the situation when one or more actuators are failed during the service. It is a situation with serious consequences for the process and which can have catastrophic result. To simulate this case, we consider the modify structure represented in figure 2.
In this figure, $u_{r1} \ldots u_{rn}$ represent the real inputs of the process. The expression of $u_{ri}(t)$ is:

$$u_{ri}(t) = (1 - k_{di}) u_i(t) + k_{di} u_{di0} \tag{25}$$

If the actuator A_i is blocked in u_{di0} position, we simulate this with $k_{di}=1$. So, it is possible to write:

$$u_r(t) = (\mathbf{I} - \mathbf{K}_d) u(t) + \mathbf{K}_d u_{d0} \tag{26}$$

where

$$\mathbf{K}_d = \begin{bmatrix} k_{d1} & \dots & 0 \\ 0 & \dots & 0 \\ 0 & \dots & k_{dn} \end{bmatrix}$$
$$k_{di} = \begin{cases} 0 & \text{for fault free} \\ 1 & \text{in presence of fault} \end{cases} \quad i = \overline{1,n} \tag{27}$$

and **I** is the unit matrix. In this case the state equations of the process are

$$\dot{x}_p(t) = \mathbf{A}_p x_p(t) + \mathbf{B}_p (\mathbf{I} - \mathbf{K}_d) u(t) + \mathbf{B}_p \mathbf{K}_d u_{d0} \tag{28}$$

$$y(t) = \mathbf{C}_p x_p(t) \tag{29}$$

The output vector for the system represented fig.2 (closed loop) is:

$$\begin{aligned} Y(s) &= \left[\mathbf{I} + H_p(s)(\mathbf{I} - \mathbf{K}_d)\mathbf{K}_a D(s) C(s)\right]^{-1} \times \\ & H_p(s)(\mathbf{I} - \mathbf{K}_d)\mathbf{K}_a D(s) C(s) V(s) + \\ & + \left[\mathbf{I} + H_p(s)(\mathbf{I} - \mathbf{K}_d)\mathbf{K}_a D(s) C(s)\right]^{-1} \times \\ & \times H_p(s) \mathbf{K}_d \frac{u_{d0}}{s} \end{aligned} \tag{30}$$

where $\mathbf{K}_d$ is fault matrix. The stability of the structure is assure if and only if the solutions of the characteristic equation are located in the left half plane of complex plane s.

$$\begin{aligned} & \det\left[\mathbf{I} + H_p(s)(\mathbf{I} - \mathbf{K}_d)\mathbf{K}_a D(s) C(s)\right] = \\ & = \det\left[\mathbf{I} + H_p(s)\mathbf{K}_a D(s) C(s)\right] \times \\ & \times \det\{\mathbf{I} - \left[\mathbf{I} + H_p(s)\mathbf{K}_a D(s) C(s)\right]^{-1} \times \\ & \times \left[H_p(s)\mathbf{K}_d \mathbf{K}_a D(s) C(s)\right]\} \end{aligned} \tag{31}$$

Let be the next equations for the process in steady-state, fault free (optimal conditions), derived from (1):

$$y_{10} = k_{p11} u_{10} + k_{p12} u_{20} \tag{32}$$

$$y_{20} = k_{p21} u_{10} + k_{p22} u_{20} \tag{33}$$

Let be now u_0^{*} and respectively y_0^{*} the steady-state vectors in fault conditions. The problem is to know if exist an acceptable inputs for the rest of actuators when one of them is failed (blocked). To exemplify, consider again the case (1). Suppose that the actuator A_1 is blocked and the corresponding input is u_{d10}. In steady state, we have:

$$y_{10}^{*} = k_{p11} u_{d10} + k_{p12} u_{20}^{*} \tag{34}$$

$$y_{20}^{*} = k_{p21} u_{d10} + k_{p22} u_{20}^{*} \tag{35}$$

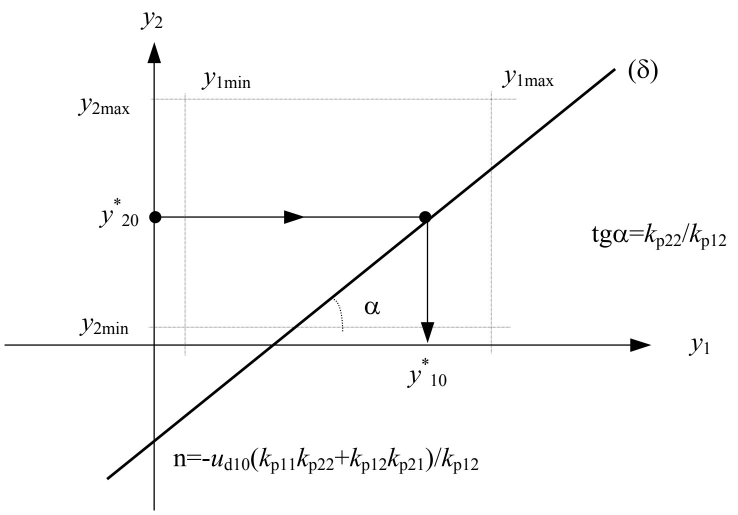

Fig. 3.

From (32) and (33) results:

$$\overset{*}{y}_{20} = \frac{k_{p22}}{k_{p12}}\overset{*}{y}_{10} - \frac{k_{p11}k_{p22} + k_{p12}k_{p21}}{k_{p12}}u_{d10} \quad (36)$$

The relation (36) represent a line (δ). We have the graphical representation in figure 3.

If the pair $(\overset{*}{y}_{10}, \overset{*}{y}_{20})$ is an acceptable solution, we have an affirmatively answer. Simultaneously, we impose the reference for the valid input:

$$\overset{*}{u}_{20} = \frac{\overset{*}{y}_{10}k_{p21} - \overset{*}{y}_{20}k_{p11}}{k_{p12}k_{p21} - k_{p11}k_{p22}} \quad (37)$$

A DESIGN EXAMPLE

The proposed approach is applied to a heat-exchanger plant, with the structure represented in figure 4. The mathematical model is:

SA1:
$$64{,}4642\frac{dT_{a1}}{dt} = -T_{a1} - 0{,}0248F_{a1}T_{a1} + 0{,}0247F_{a1}T_{ai} + T_{g3} \quad (38)$$

SG3:
$$0{,}1731\frac{dT_{g3}}{dt} = -T_{g3} - 0{,}0033F_gT_{g3} + 0{,}0035F_gT_{g2} + T_{a1} \quad (39)$$

SA2:
$$81{,}445\frac{dT_{a2}}{dt} = -T_{a2} - 0{,}063F_{a2}T_{a2} + 0{,}063F_{a2}T_{a1} - 0.138W_{inj1} + T_{g1} \quad (40)$$

SG1:
$$0{,}204\frac{dT_{g1}}{dt} = -T_{g1} - 0{,}0374F_gT_{g1} + 0{,}0425F_gT_{gi} + T_{a2} \quad (41)$$

SA3:
$$21{,}7655\frac{dT_{a3}}{dt} = -T_{a3} - 0{,}027F_{a3}T_{a3} + 0{,}0026F_{a3}T_{a2} - 0.0111W_{inj2} + T_{g2} \quad (42)$$

SG2:
$$0{,}0295\frac{dT_{g2}}{dt} = -T_{g2} - 0{,}001F_gT_{g2} + 0{,}0015F_gT_{g1} + T_{a3} \quad (43)$$

and

$$F_{a3} = F_{ai} + W_{inj1} + W_{inj2} \quad (44)$$

$$69{,}6\frac{dF_{a2}}{dt} = -F_{a2} + F_{a3} - W_{inj2} \quad (45)$$

$$11.13\frac{dF_{a1}}{dt} = -F_{a1} + F_{a3} - W_{inj1} - W_{inj2} \quad (46)$$

We can attach a matrix of transfer to the liniarised model in steady state point, for constants inputs ($T_{gi} = ct., T_{ai} = ct., F_g = ct., F_{ai} = ct.$). So we have:

$$\begin{bmatrix} T_{a2}(s) \\ T_{a3}(s) \end{bmatrix} = \begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} \cdot \begin{bmatrix} W_{inj1}(s) \\ W_{inj2}(s) \end{bmatrix} \quad (47)$$

In steady state we have:

$$\overset{*}{T}_{a20} = k_{11}\overset{*}{W}_{inj10} + k_{12}\overset{*}{W}_{inj20} \quad (48)$$

$$\overset{*}{T}_{a30} = k_{21}\overset{*}{W}_{inj10} + k_{22}\overset{*}{W}_{inj20} \quad (49)$$

Suppose that the first actuator is failed and the proper output, for the same command of D.U., has the value W_{injd10}, which is different by the correct value $\overset{*}{W}_{inj10}$.

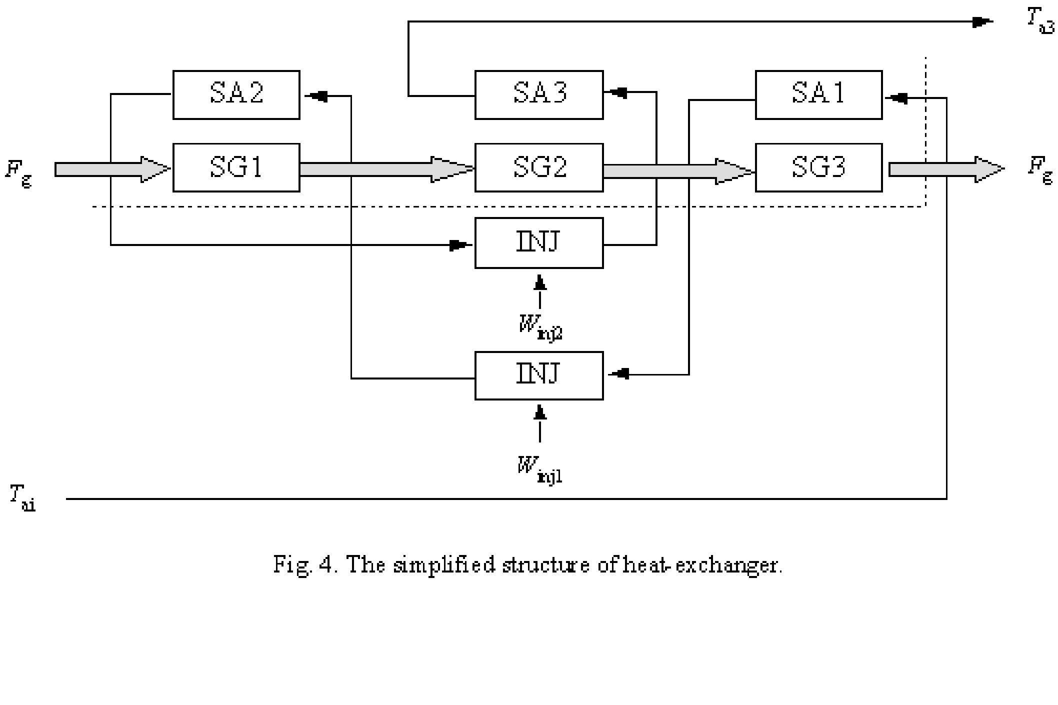

Fig. 4. The simplified structure of heat-exchanger.

In these conditions, we have:

$$T_{da2} = k_{11}W^*_{injd10} + k_{12}W^*_{inj2} \quad (50)$$

$$T_{da3} = k_{21}W^*_{injd10} + k_{22}W^*_{inj2} \quad (51)$$

To maintain the same value for the final temperature (T^*_{a3}), result for the second input (in fault condition) the value:

$$W_{inj2} = \frac{k_{21}T_{da2} - k_{11}T^*_{a3}}{k_{12}k_{21} - k_{11}k_{22}} \quad (52)$$

If this value is technological acceptable for the process, we try to obtain this command. One possibility is to keep the same structure (fig. 1) but we can modify the D.U. block to preserve the interinfluence between channels, very usefully in actuator fault conditions.

CONCLUSIONS

In this paper, the authors propose some practical behaviour in control and supervising of complex process (MIMO), in presence of actuators faults.

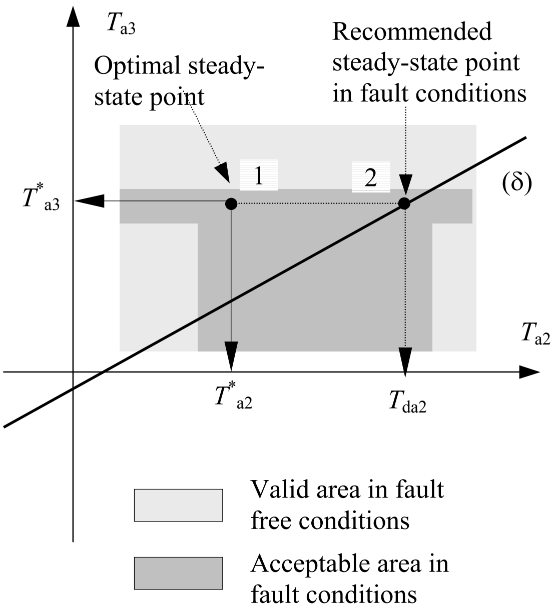

Fig. 5. The control in failure conditions has an acceptable solution.

We have considered the case when one or more actuators are blocking in a fixed position or are not supplied (in this case the servomechanism are in the total closed or total open position). The immediate goals is to preserve the stability of process and, if is possible, to control the process in a slightly degraded manner.
We propose a method to find the new values for the valid commands, in presence of a failed actuator. To control the process with less commands like usually, it is necessary to preserve the interinfluence between the channels.
It is very important to say that this method just offers a possibility to action in failure conditions and is not generally valid. The position of blocked actuator modify the position of (δ) line like in fig. 5 and 6.

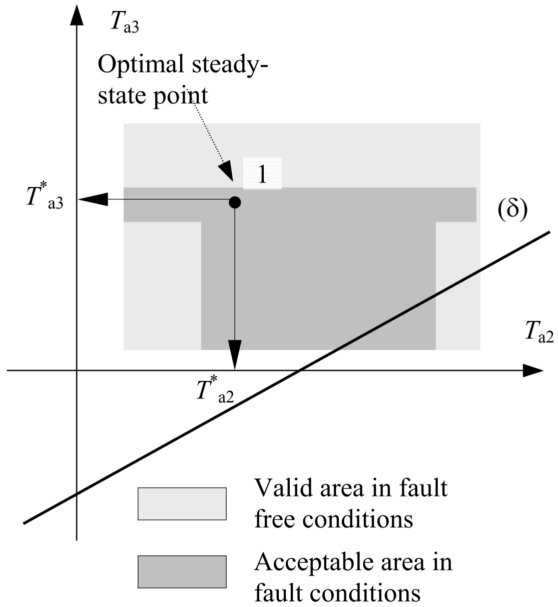

Fig. 6. The control in failure conditions do not has an acceptable solution.

REFERENCES

Chow, E. Y., A. S. Willsky, (1984) Analytical redundancy and the design of robust failure detection systems, *IEEE Trans. Aut. Contr.*, vol. AC-29, no. 7, p. 603 – 614.

Iancu, E., (1996), Détection et localisation analytique des actuateurs déteriorés, SINTES 8, p.107-112, Universitatea din Craiova.

Iancu, E., M. Vinatoru (1999), *Detectia si localizarea defectelor in sistemele dinamice*, Editura SITECH, Craiova.

Vinatoru, M., E. Iancu, C. Vinatoru, (1997), *Robust control for actuator failures*, 2nd IFAC Symposium ROCOND'97, Budapest, p. 537-542.

Vînătoru, M., E. Iancu, C. Vînătoru, R.J.Patton, J. Chen, (1998), *Fault Isolation Using Inverse Sensitivity Analysis*, International Conference on Control'98, 1-4 September 1998, University of Wales, Swansea, England, vol. 2, p. 964-968.

Willsky, A. S. (1976), A survey of design methods for failure detection in dynamic systems, *Automatica*, vol. 12, no. 6, p. 601-611.