Design of multivariable control systems using Antisystem-Approach

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Abstract: *In this paper is introduced an approach of analysis and design of control systems for multi-input multi-output (MIMO) plants and illustrated with one simple example programed for PLC Freelance 800F of ABB.*
This approach, which was first published in [Kattanek&Sacharjan, 1968] as «Compression of variables» for multi-stage multi-dimensional allocation processes, was called later [Zacher, 2003] «Antisystem-Approach» (ASA). Based upon duality principles ASA can be commonly used in such fields as ordinary calculus of proportions, by mathematical tasks like solution of partial differential equations and optimization problems as well as in applied fields of electrical and chemical engineering. A brief overview of ASA applications by open-loop and closed-loop MIMO control is given in the presented paper. More info by www.szacher.de.
Keywords: *Closed-loop control (CLC), Multi-input multi-output processes (MIMO), programmable logical control (PLC)*

1. Introduction

For all efforts in development of control theory and success of informatics the «Curse of dimensionality» [Bellman, 2003] is not yet overcome. With this term Richard Bellman, known as a discoverer of the mathematical optimization method called dynamic programming, decribed the problem caused by the exponential increase of calcualtions associated with adding some extra dimensions to the mathematical description of a system. The problems, which can be easy solved with known methods by low dimensions, require vastly more computer time when there are more state variables in the system.

The similar remark could be done concerning multi-input multi-output control (MIMO). Many industrial processes can be divided into sub processes and variables can be grouped into several sets corresponding to each subsystem, building a MIMO plant. This division corresponds to actually engineered subsystems and, in other cases; it is just a conceptual framework for control design. The MIMO control for such processes is very well studied; the design methods are developed and described, for example by [Korn, 2000], [Lunze, 2005], [Schulz, 2002], but the practical use is complicated becouse of the dimension of the system. Most of known industrial applications control separate subsystems ignoring interaction amongst subsystems inside the MIMO plant.

The commonly used methods for MIMO closed-loop control are state space feedback and observer design. Based upon pole placing concept these methods are universal and efficient, but the plant dimension more as $n = 3$ makes difficultt the description of loops.

The design technique with transfer functions, which is widely used for single-input single-output systems (SISO), is only by MIMO plants with two inputs and two outputs possible. But also in this case the design could not be done with the same precision as for SISO. The controller tuning for not real, but an equivalent plant, known as diagonal controller [Reuter&Zacher, 2008], is sufficient only for steady state values. The dynamic behaviour will be ingored to reduce the calculations; as a result the quality of such control is not sufficient. The next problem by diagonal controller is that the disturbance behaviour is not studied enough.

The decoupling of MIMO subsystems with special MIMO controllers brings the best results, but the realisation is complicated because of derivative parts, which occur by decoupoling. The industrial MIMO plants consist usually of proportional blocks with delay or with dead time. The reciprocal of such blocks, which are needed for decoupling, are not realizable. From this reason the decoupling blocks will be simplified, which reduces the quality of control.

Concluding the brief overview of problems by the MIMO controls design we could mention the nessesity of the developments in this field. A new approach is introduced in this paper, simulated and illustrated with one simple example programed for PLC Freelance 800F of ABB.

2. Duality and Antisystems

Dual means a thing having or composed of two parts, a twofold thing. According to the philosophical theory of dualism the world is dual, because it is ultimately explicable in terms of two basic entities as mind and matter.
The review of duality in the mathematics, electricity and in the control systems theory is given in the book [Zacher, 2003]. It is shown, that the closed-loops for the feedback control of industrial processes have also a dual nature; they handle with the energy and substance treating information to achieve the desired results (Fig. 1). It turns out that each control process consists of two closed loops, one for the energy and substance, another for the information. The difference between them is that the energy and substance lay under balance equations; the information's treatment has no balances.

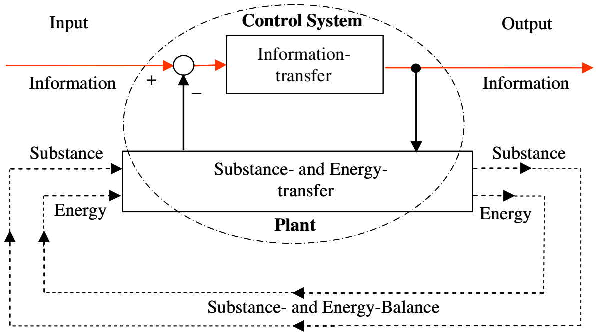

Fig. 1. Duality of feedback control for industrial processes

If a dual system is based upon two mutually antagonistic principles it can be composed in a system and an antisystem. The prefix *anti* means *against*, forming a system derived from the original system but acting against it. According to this definition each system has its antisystem, which is the same as the original system, but operating in the opposite direction.

The examples of antisystems can be found in the physics, like particles and antiparticles, electrons and positrons, negative and positive charges.
The antisymmetry is described by [Sirvardiere, 1995] as the dual symmetry operation, which counteracts against the original symmetry operation. Based upon the same principle there are known colors and anticolors, the sounds and antisounds.
The proportions and antiproportions are used in the book [Zacher, 2008] to simply the solutions of some tasks in the elementary mathematics and to develop a new concept for the solution of the linear algebraic equations. For example, the system

$$\begin{cases} 2x_1 + 3x_2 = c_1 \\ 4x_1 + 5x_2 = c_2 \end{cases} \quad \text{with given factors} \quad \begin{matrix} c_1 = 28 \\ c_2 = 48 \end{matrix}$$

will be solved by building the antisystem

$$\begin{cases} 2z_1 + 4z_2 = d_1 \\ 3z_1 + 5z_2 = d_2 \end{cases} \quad \text{with calcualted} \quad \begin{matrix} z_1 = 1 \\ d_2 = 0 \end{matrix} \quad \text{and} \quad \begin{matrix} z_2 = -0{,}6 \\ d_1 = -0{,}4 \end{matrix},$$

so that the following balance exists:

$$d_1 x_1 + d_2 x_2 = c_1 z_1 + c_2 z_2$$

The last equation gives the answer: $x_1 = 2$.
Characteristic for the interaction of a system with its antisystem is a balance, which compensates both, bringind the whole composition to the equilibrium, similar to the balance of two powers acting in opposite directions. Some simple examples are mentioned by [Zacher, 2003]: supposing a regular quadratic matrix $\boldsymbol{A}$ as a system and its inverse matrix $\boldsymbol{A}^{-1}$ as an antisystem an equilibrium condition could be found, namely, the unit matrix $\boldsymbol{I}$:

$$\boldsymbol{A} \cdot \boldsymbol{A}^{-1} = \boldsymbol{I}$$

The trigonometric functions sine and cosine are also a system and an antisystem, because they underlay the balance equation:

$$\sin^2 t + \cos^2 t = 1$$

Simulated with wave generators *sin*(t) and *sin*(t+π/2) they lose the balance, if a disturbance occurs [Zacher, 2003].

3. Antisystems by feedback control

Referred to the feedback control means that an antisystem to the controller is the same controller but counteracting in opposite direction as shown in Fig. 2. It is seen, that the control system and antisystem build a new closed-loop with the certain balance for the information like it is the case by the energy and substance.

The main idea of the antisystem approach (ASA) is to use the equations with balance-variables, which are scalars, instead of original equations with original control variables, which are vectors of the dimension n. By n = 1 ASA has no advantages against conventional analysis with original vectors. The bigger is n, the more reduction is expected from calculations with ASA.

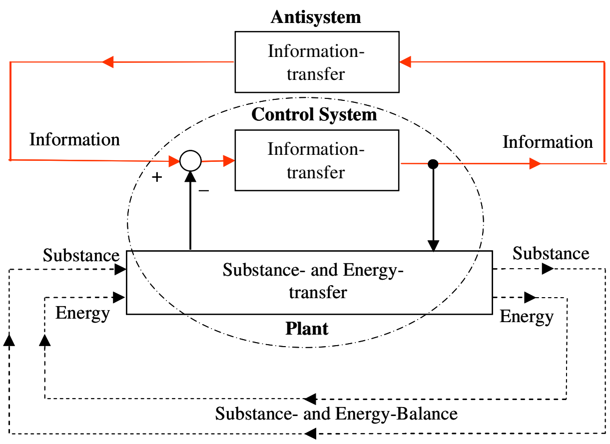

Fig. 2. Antisystem as a part of a feedback control system

For example, if the system with transfer function $G_S(s)$ and the antisystem with transfer function $G_M(s)$ are given, as shown in Fig. 3, then the following balance between them exists for all values of input signals $y(s)$ and $w_x(s)$

$$e_y = e_x \,,$$

if the following condition is fulfilled:

$$G_S(s) = G_M(s)$$

The balance variables e_y and e_x are errors, although they are no differences

$$e_y = y - w_y$$
$$e_x = x - w_x$$

as usual, but products:

$$e_y = y w_y$$
$$e_x = x w_x$$

Considering

$$x = G_S(s)\, y$$
$$w_y = G_M(s)\, w_x$$

it is easy to show, that the balance eqution is:

$$w_y y = w_x x$$

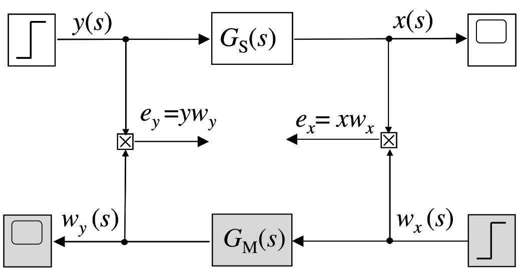

Fig. 3. Block-diagramm of a system and antisystem

This approach was used by [Zacher, 2000] for multi-stage multi-dimensional allocation plants. The MIMO-plant, shown in Fig. 4, consists of N subsystems (stages), each of them transfers the input vectors $\boldsymbol{X}_{i-1}$ to the output vectors $\boldsymbol{X}_i$ with the transfer operations $\boldsymbol{A}_i$, which are (n, n)-matrices:

$$\boldsymbol{X}_i = \boldsymbol{A}_i \boldsymbol{X}_{i-1}$$

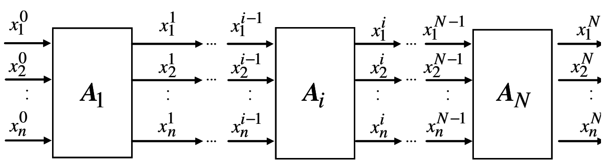

Fig. 4. MIMO-plant with n variables and N stages

To the each subsystem is introduced a sub-antisystem, like shown in Fig. 5, with transposed input vectors $\boldsymbol{W}_i$ and transposed output vectors $\boldsymbol{W}_{i-1}$ with the same transfer operations $\boldsymbol{A}_i$, which is transposed matrix $\boldsymbol{A}_i^{\mathrm{T}}$:

$$\boldsymbol{W}_{i-1} = \boldsymbol{A}_i^{\mathrm{T}} \boldsymbol{W}_i$$

The balance between the system and the antisystem is a scalar product:

$$\boldsymbol{W}_{i-1} \boldsymbol{X}_{i-1} = \boldsymbol{W}_i \boldsymbol{X}_i$$

If we apply to the block-diagram of Fig. 5 the definitions of artificial neural networks, then the signal transfer of the original system will be called *forward propagation*, the signal transfer of the antisystem *backpropagation* and the transfer of errors e_i is *cross propagation*.

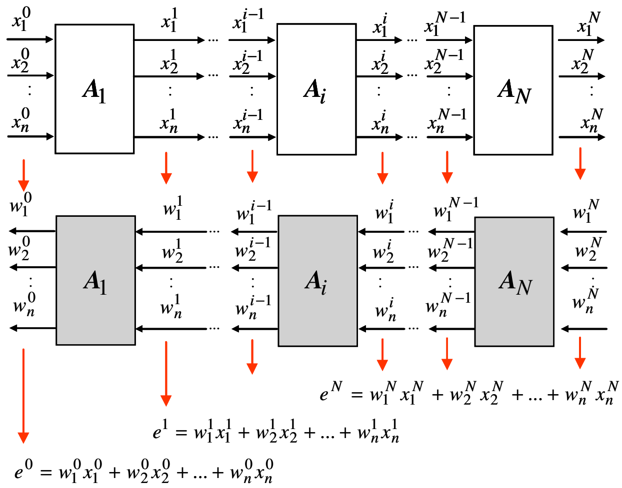

Fig. 5. MIMO plant as a system and its antisystem

4. Example of MIMO system-antisystem balance

To confirm the balance between the system and antisystem the following example was simulated.

The MIMO plant with transfer matrix $\boldsymbol{G}_S(s)$ with subsystems $G_{11}(s)$, $G_{12}(s)$, $G_{21}(s)$, $G_{22}(s)$ is given in P-canonical form as shown below in Fig. 6.

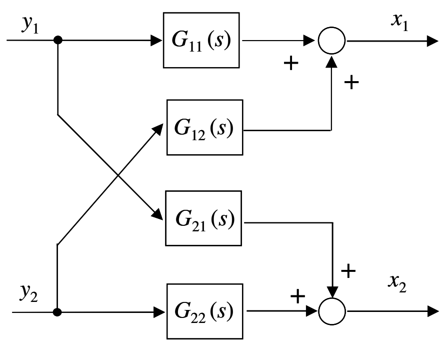

Fig. 6. Example of MIMO plant in P-canonical form

$$G_{11}(s) = \frac{x_1(s)}{y_1(s)} = \frac{K_{PS11}}{1+sT_{11}}$$

$$G_{12}(s) = \frac{x_1(s)}{y_2(s)} = \frac{K_{PS12}}{1+sT_{12}}$$

$$G_{21}(s) = \frac{x_2(s)}{y_1(s)} = \frac{K_{P21}}{1+sT_{21}}$$

$$G_{22}(s) = \frac{x_2(s)}{y_2(s)} = \frac{K_{P22}}{1+sT_{22}}$$

The antiplant is shown in Fig. 7. It consists of the same subsystems building the transposed transfer matrix $\boldsymbol{G}^T(s)$ with the backpropagation from inputs W_{x1}, W_{x2} to the outputs W_{y1}, W_{y2}.

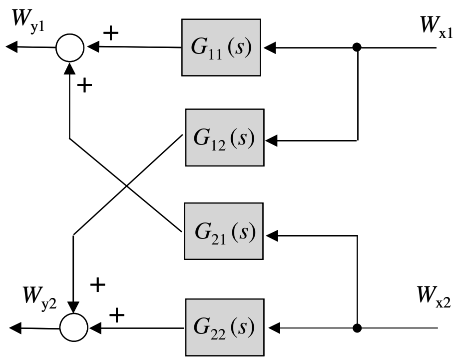

Fig. 7. MIMO antiplant to the example of Fig. 6

The balance between errors of the plant and antiplant takes place:

$$e_y(s) = e_x(s)$$

$$e_x(s) = W_{x1}(s)x_1(s) + W_{x2}(s)x_2(s)$$
$$e_y(s) = W_{y1}(s)y_1(s) + W_{y2}(s)y_2(s)$$

It should be noted, that the inputs W_{x1} and W_{x2} of the anti-plant will be chosen arbitrarily.
Supposing the transfer matrix of the MIMO-plant $\boldsymbol{G}_S(s)$ is

$$\boldsymbol{G}_S(s) = \begin{pmatrix} \frac{3}{1+s} & \frac{2}{1+4s} \\ \frac{1}{1+5s} & \frac{4}{1+3s} \end{pmatrix}$$

the transfer matrix $\boldsymbol{G}_M(s)$ of the antisystem will be defined as transposed matrix for $\boldsymbol{G}_S(s)$:

$$\boldsymbol{G}_M(s) = \begin{pmatrix} \frac{3}{1+s} & \frac{1}{1+5s} \\ \frac{2}{1+4s} & \frac{4}{1+3s} \end{pmatrix}$$

The step responses of errors e_x and e_y by the arbitrarily chosen input steps y_1, y_2 and W_{x1}, W_{x2} are shown in Fig. 8. The difference between e_x and e_y is less then 10^{-14} and is practically equal to zero.

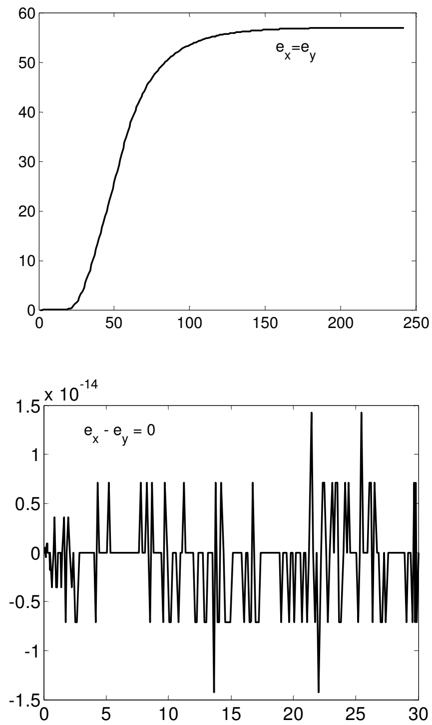

Fig. 8. Step responses and balance of errors e_x and e_y

5. Open loop control with ASA

In the steady state by $t \to \infty$ the balance simplifies to:

$$e_y(\infty) = e_x(\infty)$$

$$x_1(\infty)W_{x1} + x_2(\infty)W_{x2} = W_{y1}(\infty)y_1 + W_{y2}(\infty)y_2$$

Choosing the inputs properly the open-loop control scheme could be designed. Considering that the goal of the control is achieved (controlled variables x_1 and x_2 are equal to set points w_1 and w_2) and that the set points of the plant w_1 and w_2 are the same as for the antiplant W_{x1} and W_{x2}, we get the following expressions for steady state (the sign ∞ will be neglected by writing):

$$x_1 = W_{x1}$$
$$x_2 = W_{x2}$$

The balance of errors transforms to the following:

$$W_{x1}^2 + W_{x2}^2 = W_{y1}y_1 + W_{y2}y_2$$

From the last expression we can calculate the actuating variables y_1 and y_2, which are applied to the plant, under consideration of one of two plant equations:

$$x_1 = K_{P11}y_1 + K_{P12}y_2$$
$$x_2 = K_{P21}y_1 + K_{P22}y_2$$

For example, taking the second equation, we build the following equations system:

$$\begin{cases} K_{P21}y_1 + K_{P22}y_2 = x_2 \\ W_{y1}y_1 + W_{y2}y_2 = W_{x1}^2 + W_{x2}^2 \end{cases}$$

Finaly the following equations system will be obtained to define the actuating signals y_1 and y_2:

$$\begin{cases} K_{P21}y_1 + K_{P22}y_2 = W_{x2}^2 \\ W_{y1}y_1 + W_{y2}y_2 = W_{x1}^2 + W_{x2}^2 \end{cases}$$

Putting a new variable E_x into consideration

$$E_x = W_{x1}^2 + W_{x2}^2$$

we solve this equations system:

$$y_1 = \frac{\begin{vmatrix} W_{x1}^2 + W_{x2}^2 & W_{y2} \\ W_{x2} & K_{P22} \end{vmatrix}}{\begin{vmatrix} W_{y1} & W_{y2} \\ K_{P21} & K_{P22} \end{vmatrix}} = \frac{E_x K_{P22} - W_{x2}W_{y2}}{W_{y1}K_{P22} - W_{y2}K_{P21}}$$

$$y_2 = \frac{\begin{vmatrix} W_{y1} & W_{x1}^2 + W_{x2}^2 \\ K_{P21} & W_{x2} \end{vmatrix}}{\begin{vmatrix} W_{y1} & W_{y2} \\ K_{P21} & K_{P22} \end{vmatrix}} = \frac{W_{x2}W_{y1} - E_x K_{P21}}{W_{y1}K_{P22} - W_{y2}K_{P21}}$$

The structure of the open-loop control system realizing this calculation scheme shown in Fig. 9. The system reacts with acceptable overshoots (Fig. 10).

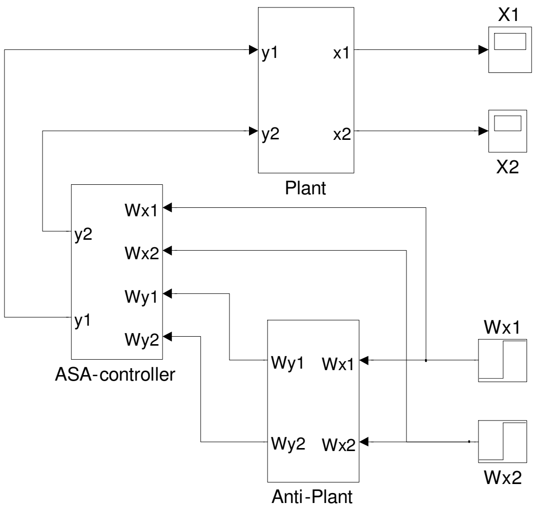

Fig. 9. Block diagram of the open-loop control with ASA

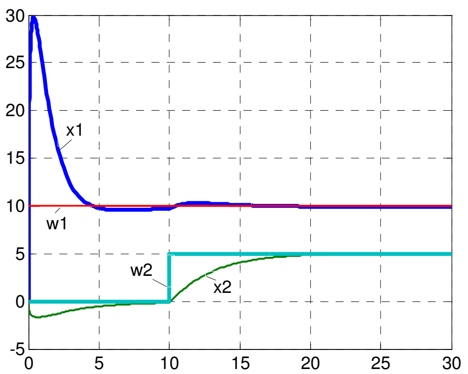

Fig. 10. Step responses by non-simultaneous input steps

6. Closed-loop control with ASA

Considering the same plant as in the previous section let us design a closed loop control for it. In [Zacher, 2010] is decribed how to create the derivative blocks with ASA.

Supposing the inputs of the plant

$$y_1 = y_2 = 1$$

and inputs of the antiplant

$$W_{x1} = W_{x2} = W_x$$

the following expressions for the products of cross variables y_{c1} and y_{c2} will be achieved

$$y_{c1} = y_2 W_{y1}(s) = G_{12}(s)W_x + G_{22}(s)W_x$$

$$y_{c2} = y_1 W_{y2}(s) = G_{11}(s)W_x + G_{21}(s)W_x$$

or

$$y_{c1} = \frac{K_{D1}(1+sT_{D1})}{(1+sT_{12})(1+sT_{22})}W_x$$

$$y_{c2} = \frac{K_{D2}(1+sT_{D2})}{(1+sT_{11})(1+sT_{21})}W_x$$

with parameters:

$$K_{D1} = K_{P12} + K_{P22} \qquad T_{D1} = \frac{K_{P12}T_{22} + K_{P22}T_{12}}{K_{P12} + K_{P22}}$$

$$K_{D2} = K_{P11} + K_{P21} \qquad T_{D2} = \frac{K_{P11}T_{21} + K_{P21}T_{11}}{K_{P11} + K_{P21}}$$

The reciprocal of y_{c1} and y_{c2} have dynamic characteristics of the PD-T1-blocks:

$$y_{c1}^* = \frac{1}{y_{c1}} = \frac{1}{K_{D1}} \cdot \frac{(1+sT_{12})(1+sT_{22})}{1+sT_{D1}}W_x$$

$$y_{c2}^* = \frac{1}{y_{c2}} = \frac{1}{K_{D2}} \cdot \frac{(1+sT_{11})(1+sT_{21})}{1+sT_{D2}}W_x$$

For the given plant

$$G_{11}(s) = \frac{3}{1+s} \qquad G_{12}(s) = \frac{2}{1+4s}$$

$$G_{21}(s) = \frac{1}{1+5s} \qquad G_{22}(s) = \frac{4}{1+3s}$$

the parameters of the PD-T1-blocks are:

$$K_{D1} = K_{P12} + K_{P22} = 6$$

$$T_{D1} = \frac{K_{P12}T_{22} + K_{P22}T_{12}}{K_{P12} + K_{P22}} = 3{,}7$$

$$K_{D2} = K_{P11} + K_{P21} = 4$$

$$T_{D2} = \frac{K_{P11}T_{21} + K_{P21}T_{11}}{K_{P11} + K_{P21}} = 4$$

The simulated step responses are shown in Fig. 11. The simulation was done by the model of Fig. 12.

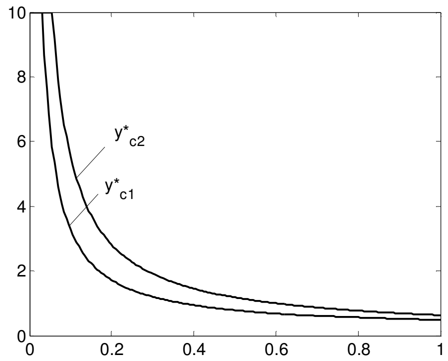

Fig. 11. Simulated step responses as PD-T1-blocks

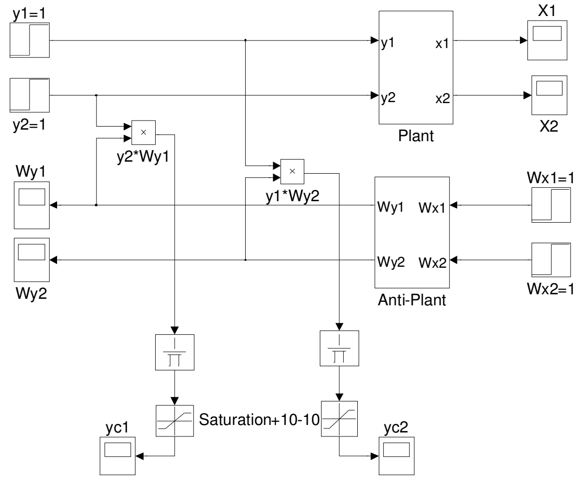

Fig. 12. PD-T1-blocks created with plant and antiplant

Since there is the possibility to create PD-T1 blocks with ASA using the plant and antiplant we can apply these PD-T1-blocks for the closed-loop control.

In Fig. 13 is given an example of the closed-loop control of a MIMO plant with such PD-T1 controllers. To eliminate the retained error here are also I-blocks applied. Significant, that by the design no calculations of the controller parameters were done. The actuating signals are produced by the steps W_{x1}, W_{x2}, which activate the antiplant. The values of W_{x1}, W_{x2} are chosen in this example $W_{x1}= 1$ and $W_{x2} = 1$; generally they differ from set points values w_1, w_2.
However the values W_{x1} and W_{x2} influence the parameters of the created PD-T1-controllers. The behaviour of the closed-loop could be improved by appropriative adjustment of W_{x1}, W_{x2} and saturations.

In the Fig. 14 are given step responses of the closed-loop with ASA to the controlling structure shown in Fig. 13. The control of own main outputs is well done, with the damping of 0,5; but the influence of cross connections is significant, because the control is resulting from the interaction between plant and antiplant.

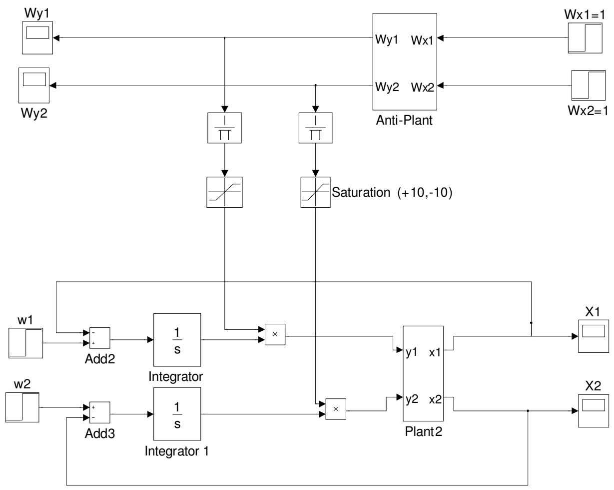

Fig. 13. Closed-loop with PD-T1 controllers using ASA

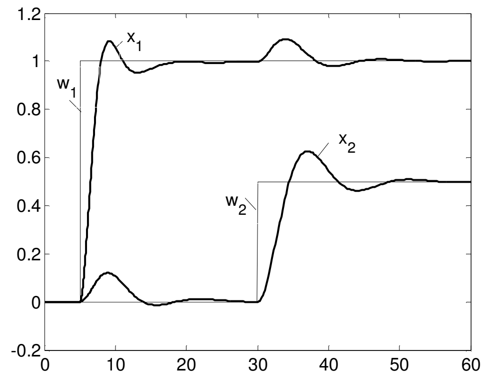

Fig. 14. Step responses of the closed-loop with ASA

To improve the dynamic behaviour the PI-controllers were applied instead of I-blocks in each single loop. The PI-controller were compensated with delays

$$T_{12} = 4 \qquad T_{21} = 5$$

of cross connections to reduce the influence (Fig. 15).
Comparing the closed-loop control with and without ASA the same conclusion can be made, like mentioned above: the bigger the dimension of the plant is, the more advanteges of ASA can be seen.

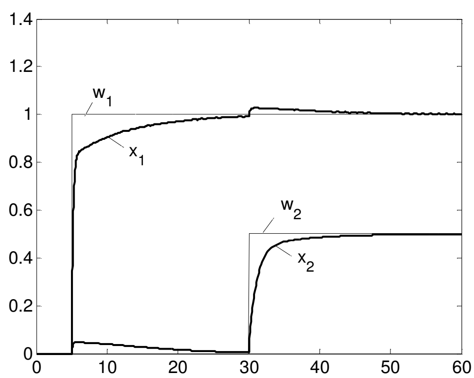

Fig. 15 Improved step responses

7. Application for the color separation plant

The device for the separation of the color-fluid from the water-mix is shown in Fig. 16. This process is designed for laboratories and is considered to be used by the teaching of the control and PLC basics. The identified plant and created antiplant are shown in Fig. 17 and 18.

The separation of two fluids obtains with the molecular filter under certain flow and pressure on the filter. The control of flow and pressure during color separation are considered as important variable because change in any one of them is going to affect other appreciably.

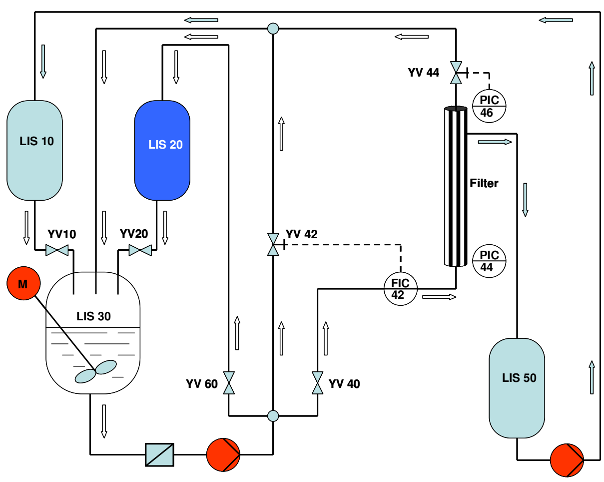

Fig. 16 Schematic diagram of color separation process

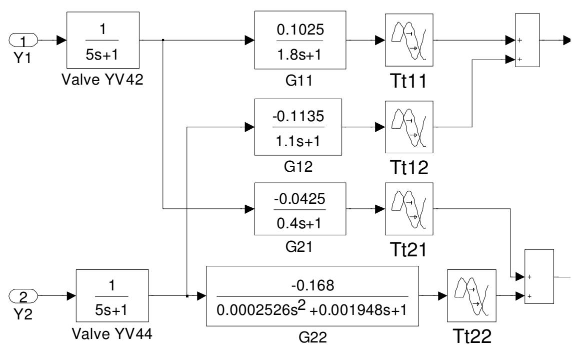

Fig. 17. MIMO-Plant simulated by MATLAB/Simulink

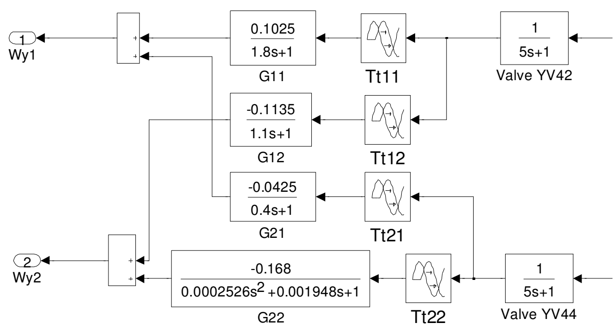

Fig. 18. Antiplant as a part of the ASA controller

Since there are two variables to be controlled also two input-two output MIMO control system is needed (Fig. 19). It is desired that change in set-point of pressure is not going to affect set-point of flow and vice versa.

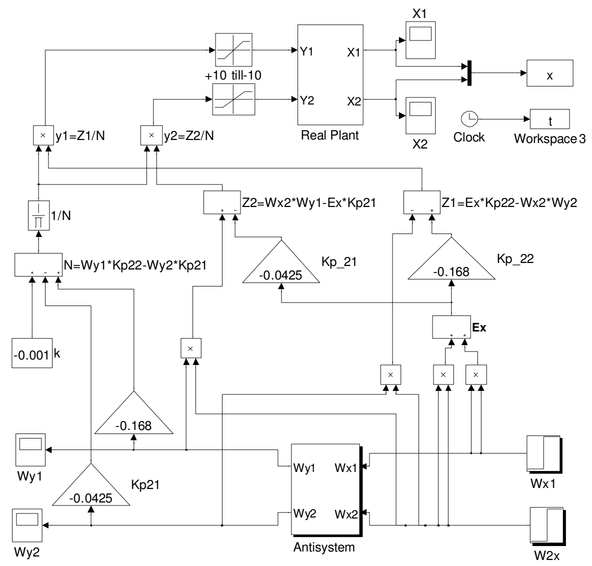

Fig. 19. Control of color separation plant using ASA

The simulation results are shown in Fig. 20. It can be seen that output x_1 by ASA control tracks both inputs W_{x1} and W_{x2} much better as it is the case by decoupled MIMO controller. Both, flow and pressure, settles within 20-30 sec without steady state error. The step response of output x_2 by ASA control is also well, the overshooting by the step W_{x2} could be reduced, if needed, increasing the saturation of the actuating value y_2.

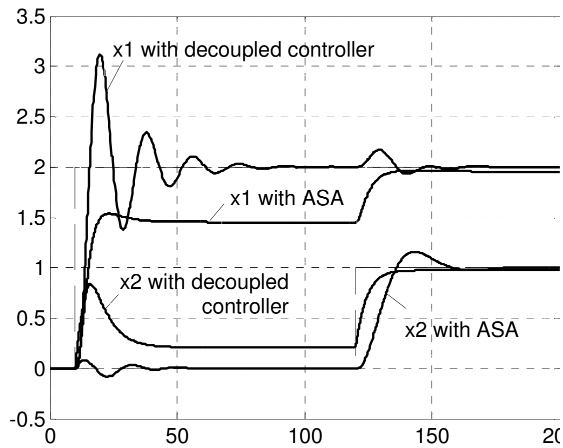

Fig. 20. Comparison of ASA open-loop control with MIMO-decoupled closed-loop control

Finally the ASA open-loop control was applied to the color separation plant using industrial PLC Freelance 800F of ABB [Saeed, 2010]. As an example the program of the pressure controller is shown in Fig. 21.

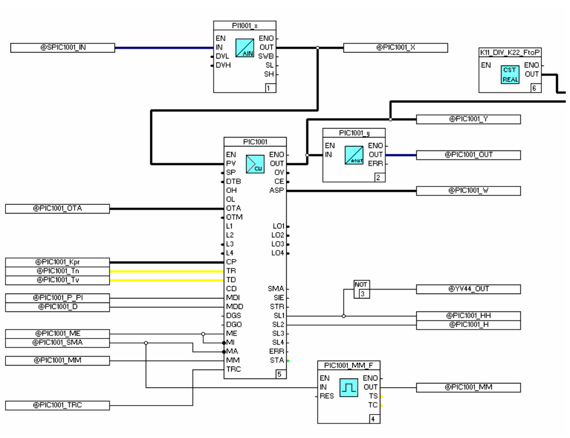

Fig. 21. Pressure controller with Freelance 800F of ABB

Fig. 6.22 shows the trend window for step responses by simultaneously applied steps of set points of the same value:

$$W_{x1} = W_{x1} = 0{,}5$$

It is seen, that flow and pressure tracks set-point well and settles within 10 till 15 sec with flow having some acceptable overshoot. The difference in flow behaviour is due to fact that Freelance in-built blocks are different than by the simulation, as it was also the case by the realization of decoupled MIMO controller.

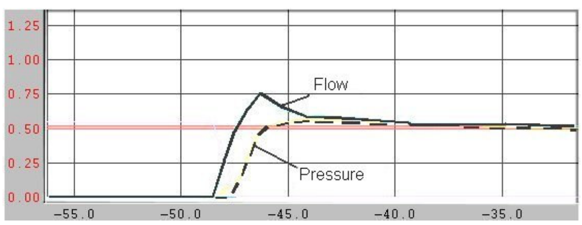

Fig. 22 ASA-Realisation with Freelance 800F of ABB

However there are two problems by realising ASA open-loop control. First of all the division $1/N$, shown in Fig. 19, could not be done by $t = 0$ because W_{y1} and W_{y2} are zero by $t = 0$, so the coefficient k should be added.

The second problem is the overshooting. Since the controller calculates steady state values of actuating variables y_1 and y_2 without taking in account the dynamic characteristics of the plant, the dynamic behaviour is not optimized.

The unstable ASA control is impossible by a stable plant because it is an open-loop control. Otherwise are overshooting possible because the controller creates products, which easy achieve very large values. To avoid it two saturation blocks to each actuating variable were used. The effective optimization can be realized by using the compensations dynamic blocks like PI or PID, combining them with ASA control.

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