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Development of CAD for Plant-Wide Control Loop Configuration

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Abstract— **For plant-wide control, many single loop controllers are utilized. Although tuning of a control loop is focused in control theory, control loop configuration problem is more essential problem. If control loop configuration is not adequate, controller cannot be stabilized with any tuning of controller parameters. Moreover, controller can be unstable by mode change of some other controllers. These are called "inconsistency" problems and "partial inconsistency" ones. This paper introduces a CAD (Computer Aided Design) tool to analyze them. It is based on DAE (Differential and Algebraic Equations), which are commonly registered in modules of plant CAD. Because quantitative information of model parameters is not necessary for it, model building is easy even for large-scale plants. In this paper, an algorism for analysis of loop configuration is proposed and the developed CAD is illustrated.**

I. INTRODUCTION

Plant-wide control is realized with plural single loop controllers working together. The controllers are coordinated to realize stable and highly efficient operation against many kinds of disturbances and request changes. Although tuning of a control loop has been discussed in control theory, the loop configuration problem has rarely been considered.

For large-scale plants, there is possibility to occur control problems which cannot be avoided by controller tuning. In some loop configuration, the independent setting of set-point values cannot be allowed for some control loops. If such set-point changes are given, some of manipulated variables diverged to fully open or fully closed. This problem is called "inconsistency" of the control loops.

Even if the control loop configuration is "consistent" and all controllers can work together, another problem can occur. When some of controllers are turned to manual mode from auto mode, the other control loops can become out of control because of the interaction change among controllers. This problem is called as "partial inconsistency".

These problems cannot be avoided by tuning of the control parameters. The loop configuration must be changed for the prevention. Therefore, control loop configuration design is more essential than quantitative controller tuning.

Design of control loop configuration has depended on the skill based on the experience of veteran process design engineers. For large-scale plants, the consistency check of the controllers is very troublesome even for them.

In Japan, the shortage of the skill has been a big matter because of many veterans' retirement and decrease of the number of new plant construction.

Moreover, check of the partial inconsistency is almost impossible for engineers because the number of combination of auto and manual controllers becomes huge.

Several theories for "inconsistency" check have been proposed[1,2,3,4,5)]. However, they have not been applied to any real large-scale plants. One of the serious problems is difficulty of building model to apply them. For RGA[1)] the large-scale gain matrix is necessary to be identified.

We have already developed a control loop configuration tool based on Cause-Effect matrices[6)]. Because the model in the tool is qualitative, model building is much easier than numerical simulators. However, it was difficult to determine the variables, whose relationships are determined algebraic equations, as causes or effects.

In this paper, the authors developed a new computer aided controller loop configuration design tool based on DAE (Differential and Algebraic Equations). Each equipment module in the CAD (Computer Aided Design) tool contains DAE, which is commonly utilized in other CAD tools for process design or plant simulation. By combining equipment modules on the CAD window, DAE of each module are gathered and system equations of the whole plant are generated automatically. Because only qualitative information of the plant is utilized in our CAD, quantitative information such as properties of the materials, equipment sizes, controller parameters or etc. are not necessary. It is much easier than for process design CAD or for plant simulation CAD to build the plant model for our CAD. Because it is not necessary to determine which variables are causes or effects for this tool, to prepare equipment modules becomes much easier than our previous CAD.

In addition to the easiness of model building, the new function is added to the CAD. Not only "inconsistency" but also "partial inconsistency" of the control loop configuration can be judged by analyzing the relationships among the variables of large-scale DAE.

In order to deal with large-scale systems, calculation load is reduced by expressing the original nonlinear DAE structure by structure matrices.

Our CAD is realized by using Microsoft Visio and Excel. Matrix calculation and registration of DAE of each equipment module are executed in Excel.

In the next section, consistency problem of control loop configuration in detail is expressed, and the algorism for evaluating consistency is proposed in the third section. At last, an example of the CAD usage is illustrated in the fourth section.

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II. INCONSISTENCY PROBLEM OF CONTROL LOOP CONFIGURATION

In a large-scale plant, the effective plant-wide operation condition is expressed as the set of set-points of controllers. It is common that they are realized by many single loop controllers.

The control loop configuration must be designed to avoid “inconsistency” and “partial inconsistency”. These loop inconsistency problems are discussed using the two tank system shown in Figure. 1.

For a simple example of control loop configuration design, the levels of two tanks, L1 and L2, are chosen as controlled variables. Although there are four valves to be able to be manipulated, only two controlled variables are considered.

To simplify the illustration of the proposed algorithm, only tank’s level, flow rate and pressure are considered in the plant model, although there are more variables such as composition and temperature. The system equations of this plant are described as DAE in Table I.

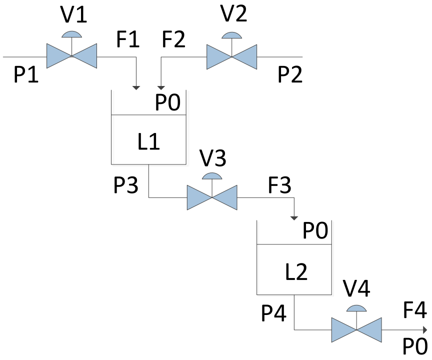

Figure 1. Example plant of two tanks system

TABLE I. DAE OF TWO TANKS SYSTEM

$\frac{dL1}{dt} = \frac{1}{A1}(F1 + F2 - F3)$
$\frac{dL2}{dt} = \frac{1}{A2}(F3 - F4)$
$P3 = P0 + \alpha \cdot L1$
$P4 = P0 + \alpha \cdot L2$
$0 = F1 - k1 \cdot V1 \cdot \sqrt{P1 - P0}$
$0 = F2 - k2 \cdot V2 \cdot \sqrt{P2 - P0}$
$0 = F3 - k3 \cdot V3 \cdot \sqrt{P3 - P0}$
$0 = F4 - k4 \cdot V4 \cdot \sqrt{P4 - P0}$

2.1. Inconsistent configuration (L1-V1, L2-V2)

As a first example of control loop configuration, V1 and V2 are paired to L1 and L2, respectively. In this case V3 and V4 are fixed. The relationship from V2 to L2 is not independent from the relationship from V1 to L1. If the set-point of L2 controller is changed, L2 cannot be stabilized at the value. Even though L2 controller manipulates V2 and the inlet flow rate F2 is changed, its effect on the level of tank1, L1, is detected by the L1 controller. L1 controller cancels the effect by manipulation of V1 and L1 returns to the original value. Because V3 is fixed and L1 is the original value, the inlet flow rate to tank 2, F3, is the original value. Because V4 is fixed and inlet flow rate F3 is original value, L2 also returns to the original value. Therefore, L2 controller cannot realize the set-point change. V2 will diverge to fully open or fully closed. This phenomenon occurs regardless of the controller parameter tuning.

This “inconsistency” can be analyzed by paying attention to dependency of the effects of MVs on PVs. In this case, the effects of V1 on L1 and L2 are dependent to the effects of V1 on L1 and L2. Therefore, the set-points of the two controllers, (L1-V1, L2-V2), cannot be changed independently. We have to know that degree of freedom is very important to consider control loop configuration.

2.2. Partially Inconsistent configuration (L1-V4, L2-V3)

As the next example, pairings (L1-V4, L2-V3) are chosen. V1 and V2 are fixed in this case. The inlet flow rates into tank 1, F1 and F2, are fixed. When the set-point of L1 is increased, V4 is decreased by L1 controller. Then, L2 is increased. By L2 controller, V3 is decreased to maintain L2. The effect of V3 decrease appears on L1 as increase. Therefore, these two control loops can work together.

However, when L2 controller is turned to manual mode, L1 becomes out of control although L1 controller is still in auto mode. If any change is observed in L1, manipulation of V4 is caused by L1 controller. If L1 should be increased, V4 is decreased by L1 controller. When L2 controller is in manual mode, V3 is kept constant even if L2 is increased. Therefore, the decrease of V4 cannot cause the increase of L1. If L1 controller has an integral control element, V4 diverges to fully close and tank 2 will overflow. This phenomenon occurs regardless of the controller parameter tuning.

This “partial inconsistency” can be analyzed by paying attention to effects via other controllers. The steady state values of the two tanks are determined by (1) and (2).

$$L1 = (\mathrm{k1} \cdot \sqrt{\mathrm{P1} - \mathrm{P0}} \cdot \mathrm{V1} + \mathrm{k2} \cdot \sqrt{\mathrm{P2} - \mathrm{P0}} \cdot \mathrm{V2})^2 / \mathrm{a} \cdot k3^2 \cdot V3^2 \quad (1)$$

$$L2 = (\mathrm{k1} \cdot \sqrt{\mathrm{P1} - \mathrm{P0}} \cdot \mathrm{V1} + \mathrm{k2} \cdot \sqrt{\mathrm{P2} - \mathrm{P0}} \cdot \mathrm{V2})^2 / \mathrm{a} \cdot k4^2 \cdot V4^2 \quad (2)$$

It is explained in (2) that V4 does not affect on L1 directly. However, when the control loop (L2-V3) is working, the change of L2 caused by the manipulation of V4 causes V3 manipulation by L2 controller. It causes the change of L1 and (L1-V4) controller can work.

If some controllers depend on such paths via other controllers, the control loop configuration can be “partially inconsistent”. The relationships between controlled variables

(PV) and manipulated variables (MV) at the steady state must be analyzed to check “partial inconsistency”.

Even in a very small plant such as the two tank system, “inconsistent” and “partially inconsistent” control loop configurations exist. In large-scale plants, the risk to design inconsistent or partially inconsistent control loop configuration is evaluated high. However, it is too hard to check the plant-wide control loop consistency one by one by manpower, so systematic approach is highly required.

III. DESIGN METHOD FOR CONTROL LOOP CONFIGURATION BASED ON SYSTEM EQUATIONS

We propose a systematic design method for consistent loop configuration below. In this method, the configuration’s consistency in steady state is evaluated qualitatively from DAE structure. There are many popular plant simulators. Their equipment modules have DAE. While numerical information such as material properties, equipment sizes and controller parameters are necessary to be determined for simulation, only qualitative DAE structure information is utilized in our CAD. Precise functions are not necessary for equipment modules, because what is required for control loop configuration design is to analyze the existence of the effects of MVs on PVs. Therefore, model building is much easier than the one for simulation. It is finished by combining the equipment modules on CAD display.

3.1. *Matrix Calculation to Solve Steady Equations for Evaluating Consistency*

For inconsistency check, the dependency of the effects of MVs on PVs is analyzed. If all control loops are independent, the gain matrix from MVs to PVs must be nonsingular. However, numerical information is necessary for identification of gain matrix. We tried to judge the regularity of the gain matrix by using only qualitative information.

From DAE in Table I, the matrix in Table II is generated. The rows in the matrix correspond to the equations. The columns correspond to the variables in DAE. “x” means state variables in the differential equations. “u” means input variables. “z” means the variables determined by algebraic equations. The “1” in the matrix means the entry of the variable in the equation.

At the steady state all derivatives become zero. For the analysis of the relationships at the steady states, the left three columns in Table II can be omitted, because all elements in these are zero.

TABLE II. DAE STRUCTURE OF EXAMPLE PLANT

	dx/dt		x		z						u						
	dL1/dt	dL2/dt	L1	L2	P3	P4	F1	F2	F3	F4	V1	V2	V3	V4	P0	P1	P2
0	1						1	1	1								
0		1							1	1							
0			1		1										1		
0				1	1										1		
0							1				1				1	1	
0								1				1			1		1
0					1				1				1		1		
0						1				1				1	1		

TABLE III. MATRIX FROM SYSTEM EQUATIONS USING RANDOM NUMBER

x		z						u						
L1	L2	P3	P4	F1	F2	F3	F4	V1	V2	V3	V4	P0	P1	P2
0	0	0	0	0.866	1.032	1.112	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1.087	0.567	0	0	0	0	0	0	0
1.005	0	1.46	0	0	0	0	0	0	0	0	0	1.169	0	0
0	1.06	0	1.205	0	0	0	0	0	0	0	0	0.793	0	0
0	0	0	0	0.977	0	0	0	1.455	0	0	0	1.364	1.262	0
0	0	0	0	0	1.017	0	0	0	0.505	0	0	0.657	0	1.479
0	0	1.277	0	0	0	1.32	0	0	0	1.237	0	0.93	0	0
0	0	0	0.757	0	0	0	0.672	0	0	0	0.865	0.96	0	0

TABLE IV. CALCULATION OF X AND Z AT STEADY STATE

x		z						u						
L1	L2	P3	P4	F1	F2	F3	F4	V1	V2	V3	V4	P0	P1	P2
1	0	0	0	0	0	0	0	−0.61	−0.72	−1.8	0	−1.87	−0.49	−0.83
0	1	0	0	0	0	0	0	0.233	0.274	0	−1.29	0.897	0.186	0.314
0	0	1	0	0	0	0	0	0.651	0.764	1.91	0	2.87	0.518	0.876
0	0	0	1	0	0	0	0	−0.21	−0.25	0	1.163	0.232	−0.17	−0.28
0	0	0	0	1	0	0	0	0.981	0	0	0	0.85	0.78	0
0	0	0	0	0	1	0	0	0	0.773	0	0	0.946	0	0.886
0	0	0	0	0	0	1	0	−0.62	−0.72	0	0	−1.42	−0.49	−0.83
0	0	0	0	0	0	0	1	0.27	0.317	0	0	0.622	0.215	0.364

In order to check the dependency, numerical calculation of the matrix is utilized. If sweep-out method is applied to Boolean matrix to check the dependency, independent relationships might be judged as dependent because just "1" or "0" can't interpret the difference of the coefficients in DAE. By using random number, each entry in Table II is substituted by different value as shown in Table III. In this matrix, each 1 is replaced for random number between 0.5 and 1.5.

When all DAE are independent, random numbers are useful against this problem because independent relationships are judged correctly and dependent equations can't change to independent even if random numbers are used.

The relationships among the variables at steady state are solved as shown in Table IV. Table IV is obtained by converting the matrix for “x” and “z” columns to unit matrix.

From Table IV, it can be understood that L1 is not affected by V4 or L2 is not done by V3. F1 is affected by V1, but it is not done by V2, V3 or V4. F3 and F4 are affected by V1 and V2, but are not done by V3 or V4.

Although V3 affect F3 directly, the steady state value of F3 is not determined by V3. At the steady state, F3=F4 and F1+F2=F3 must be satisfied from mass balance. F1 and F2 are inlet flow rates determined by V1 and V2. Therefore, F3 and F4 is determined regardless of V3 or V4. V3 and V4 can affect the steady state values of L1 and L2. These relationships are illustrated in Table IV.

Loop configuration can be considered by using this matrix. Gain matrix is also used to judge the consistency as with mathematical solution. Table V shows the matrix extracted from Table IV, which corresponds to the PVs and MVs of the “inconsistent” loop configuration, that is (L1-V1) and (L2-V2). The matrix is singular. It shows that the independent control of L1 and L2 using V1 and V2 is impossible. Therefore, “inconsistency” can be judged by singularity check of the matrix corresponding to PVs and MVs.

TABLE V. GAIN MATRIX OF (L1-V1,L2-V2) EXTRACTED FROM TABLE II

		MV	
		V1	V2
PV	L1	−0.61	−0.72
	L2	0.233	0.274

Table VI shows the matrix corresponding to partially inconsistent control loop configuration, that is (L1-V4) and (L2-V3). Because the gains for the loop configuration are zero, “partial inconsistency” can be detected. In order to prevent “partial inconsistency”, such loop pairing whose steady state gain is zero must be avoided

TABLE VI. GAIN MATRIX OF (L1-V4,L2-V3) EXTRACTED FROM TABLE II

		MV	
		V3	V4
PV	L1	−1.8	0
	L2	0	−1.29

As shown in these examples, “inconsistency” and “partial inconsistency” can be judged by calculating gain matrices from qualitative information, which is DAE structure.

Even for large-scale plants, whenever DAE structure can be obtained, consistency of the control loop configuration can be judged.

IV. DEVELOPMENT OF CAD TOOL

Figure 2 shows a screen copy of the CAD tool for control loop configuration design. It is developed by using Microsoft Visio and Excel. Equipment modules are prepared in the library shown in the left part of Figure 2. Each module has its DAE information which is contained in an Excel worksheet. Stream icons are also prepared. By using them, connection of equipment is determined. Each stream has the equations of the relationships between flow rate and pressure loss.

By putting equipment modules on the display and connecting them as shown in Figure 2, the DAE for the whole plant are automatically gathered.

Icons for sensors, actuators, controllers and information link between them are also prepared. By connecting sensors and actuators to the plant model, MVs and PVs are determined. By setting links between controller and sensor and ones between controllers and actuators, control loop configuration is determined. Present version of our CAD can judge the consistency of the designed control loop configuration.

V. CONCLUSION

This study enables analyzing steady-state consistency of configuration by just making plant model on CAD. If this CAD can be connected to common plant design CAD system, consistency could be analyzed from plant simulation models made for process design. Finally, we expect that plant engineers deal with control system with heeding this control loop configuration problem.

REFERENCES

[1] Bristol E.H., “On a new measure of interactions for multivariable process control,” IEEE Trans. Autom. Control. AC-11, pp.133-134, 1966.

[2] T.Umeda, K. Kuriyama and A. Ichikawa, “A Logical Structure for Process Control System Synthesis,” presented at IFAC World Congress, Helsinki, 1978.

[3] Luyben, W. L. and M. L. Luyben, “Essentials of Process Control,” McGraw-Hill, New York, USA, pp.448-452, 1997

[4] T.Hamaguchi., T. Kamiya, A. Yoneya, Y. Hashimoto and Y. Togari, “Fault diagnosis utilizing CE matrices,” in *Kagaku Kougaku Ronbunshu*, vol. 25, no. 3, pp.384-388, 1999.

[5] F.Kida, “Plant wide control system design by Process Engineers,” in *Chemical Engineering*, vol. 49, no. 2, 2004.

[6] Y. Hashimoto, Y.Naito, M.Kojima, T.Hamaguchi, J.Sun and I.Koshijima “Development of Plant-wide Control Loop Configuration Design Tool,” presented at the 6th Int. Conf. on Systetms Engineering (PSE ASIA), Kuala Lumpur, June 2013.

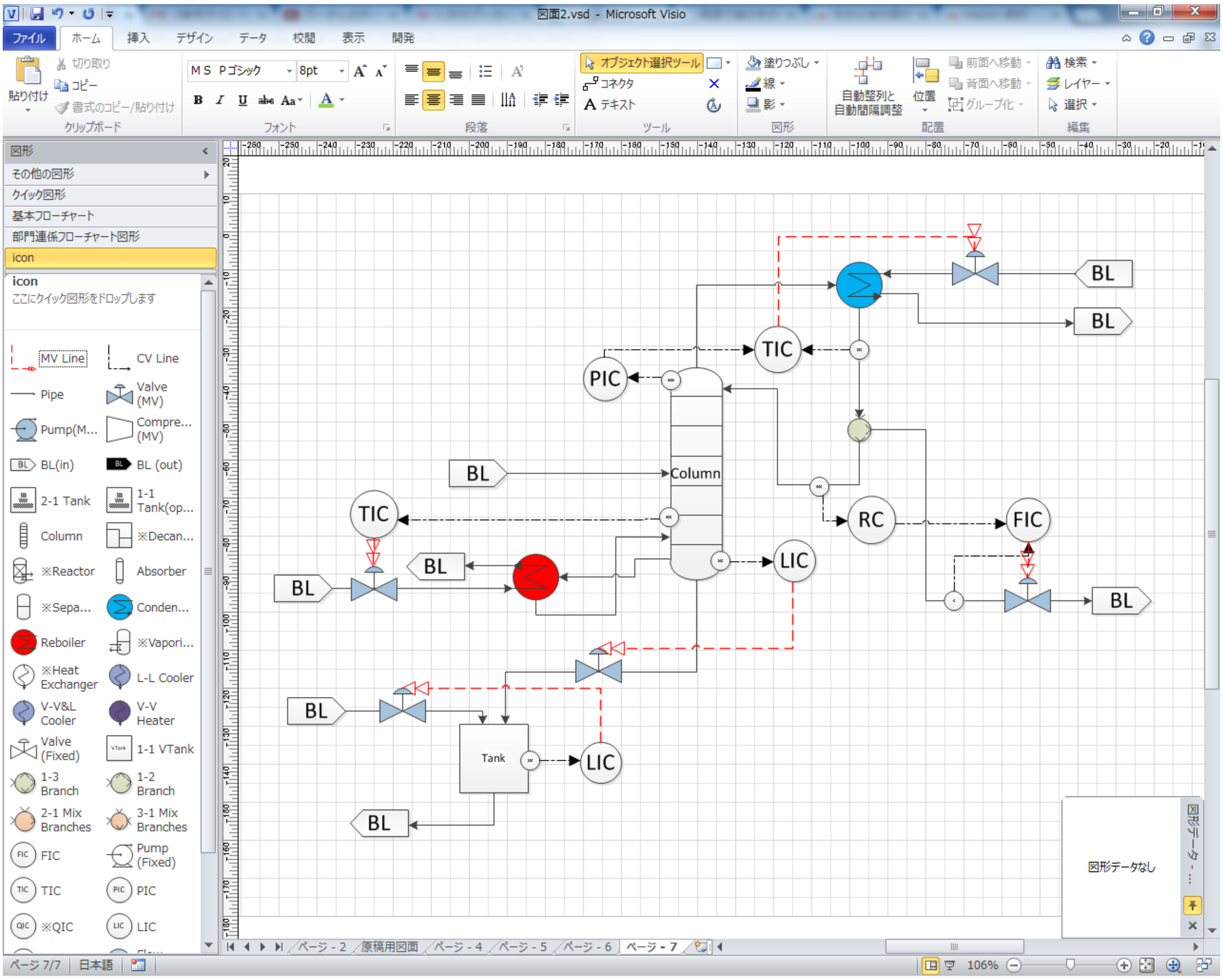

Figure 2. Example of screen shots of developed CAD tool
for control loop configuration