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Design of Effective Control Schemes for Binary Distillation Columns

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Abstract: Distillation column is very important and high consuming energy equipment in oil refineries, such that 3% of the energy consumption in the world is allocated in distillation column. The fact that let controlling the distillation column an attractive field for researcher, and hence different control schemes are proposed by researchers. In this paper we will provide a comparative study between different control schemes for a binary distillation column two simple configurations (the most known ones) (LV&DV) and two more complicated ones ((L/D,V/B) & Ryskamp's) we compare them in the basis of interactions and disturbance propagation. The mathematical models for the material balance configurations for the considered configurations are deduced using mathematical transformations (in the paper the general case of transformation between any two configurations is presented), taking the conventional configuration (LV) as a based configuration, the Dynamic Relative Magnitude Criterion (DRMC) is used to assess the interactions and disturbance propagation. The results show that the ratios control schemes are less sensitive to interactions compared with energy balance configuration LV. The same was noticed with DV configuration however other process drawbacks let it not recommended in industrial field.

Keywords: distillation, interaction, DRMC, control configurations

1. INTRODUCTION

Consider the distillation column of Fig.1 with a given feed, which has five manipulated inputs, $U = (L\ V\ B\ D\ V_T)^T$ These are all flows, and five controlled outputs $y = (x_D x_B M_D M_B\ p)^T$ These are compositions and inventories: top composition x_D , bottom composition x_B , condenser holdup M_D, reboiler holdup M_B , and pressure p. the process has poles in and or close to the origin and needs to be stabilized. In almost all cases the distillation column is first stabilized by closing three decentralized (SISO-single input single output) loops for level and pressure, involving the outputs $y_2 = (M_D M_B\, p)^T$ the remaining outputs are then the product compositions $y_1 = (x_D x_B)^T$ the three SISO loops for controlling y_2 usually interact weakly and may be tuned independently of each other.However, since each level (tank) has an inlet and two outlet flows, there exist many possible choices for u_2 (and thus for u_1). By convention, each choice ("configuration") is named by the inputs u_2 left for composition control [6],[10][11].

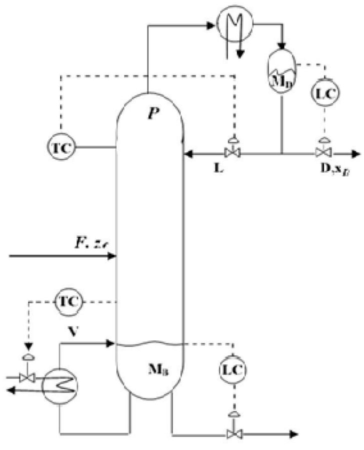


Fig.1 distillation column

2. DYNAMIC MODELING OF DISTILLATION COLUMNS

The derivation of analytical expressions requires the assumptions of

- Equilibrium stages.
- Constant relative volatility.
- Constant molar flows. As it is indicated in [5],[9]

o *Total material balance on tray i*

$$dM_i/dt = L_{i+1} - L_i + V_{i-1} - V_i \quad (1)$$

o *Material balance for light component on each tray*

$$\frac{d(M_i x_i)}{dt} = L_{i+1}x_{i+1} + V_{i-1}y_{i-1} - L_i x_i - V_i y_i \quad (2)$$

Such that M_i is the liquid holdup in the tray (i), L and V are the liquid and vapor flows respectively, and x_i & y_i are liquid and vapor compositions for light component in each tray.

o *Feed tray*

$$dM_i/dt = L_{i+1} - L_i + V_{i-1} - V_i + F \quad (3)$$

$$\frac{d(M_i x_i)}{dt} = L_{i+1}x_{i+1} + V_{i-1}y_{i-1} - L_i x_i - V_i y_i + F z_F \quad (4)$$

Where F is the feed rate and Z_F is the feed composition.

o *Total condenser*

$$dM_i/dt = V_{i-1} - L_i - D \quad (5)$$

$$\frac{d(M_i x_i)}{dt} = V_{i-1}y_{i-1} - L_i x_i - D x_i \quad (6)$$

Where D is the top product flow rate.

o *Reboiler*

$$dM_i/dt = L_{i+1} - V_i - B \quad (7)$$

$$\frac{d(M_i x_i)}{dt} = L_{i+1}x_{i+1} - V_i y_i - B x_i \quad (8)$$

Where B is the bottom product flow rate.

o *Algebraic equation :* The vapor composition y_i is related to liquid composition x_i on the same stage through the algebraic vapor-liquid equilibrium*:*

$$y_i = (\alpha x_i)/(1 + (\alpha - 1)x_i) \quad (9)$$

Where α is the relative volatility*.*

3. TRANSFORMATIONS BETWEEN DIFFERENT CONFIGURATIONS

The model for any control configuration can be compactly expressed as

$$\mathbf{\Delta y} = \mathbf{G_{yu}\Delta u} + \mathbf{G_{yw}\Delta w} \quad (10a)$$

$$\mathbf{\Delta v} = \mathbf{G_{vu}\Delta u} + \mathbf{G_{vw}\Delta w} \quad (10b)$$

Where $\mathbf{G}_{yu}$, $\mathbf{G}_{yw}$, $\mathbf{G}_{vu}$ and $\mathbf{G}_{vw}$ denote the gain matrices[4],[8] . With suitable definitions of, this model could be used to describe any control structure [7]. In general term we refer to this control structure as the "base" structure(in our case LV) and to the variables as follows: **y** is a vector of primary outputs, **u** is a vector of primary manipulators and, **v** is a vector of dependent (or secondary) manipulators, and **w** is a vector of disturbance variables. Consider now a control structure whereis the vector of primary manipulators and the vector of dependent manipulators (due to inventory control). This control structure can be described by the following model

$$\mathbf{\Delta y} = \mathbf{G_{y\psi}\Delta\psi} + \mathbf{G_{y\omega}\Delta w} \quad (11a)$$

$$\mathbf{\Delta\upsilon} = \mathbf{G_{\upsilon\psi}\Delta\psi} + \mathbf{G_{\upsilon\omega}\Delta w} \quad (11b)$$

In the general case, are some functions of **u**, **v**, and **w** that is

$$\psi = \psi\ (\mathbf{u}, \mathbf{v}, \mathbf{w}) \quad (12a)$$

$$\upsilon = \upsilon\ (\mathbf{u}, \mathbf{v}, \mathbf{w}) \quad (12b)$$

Linearization of equations (12) and introduction of deviation variables give the following relationships

$$\mathbf{\Delta\psi = H_{\psi u}\Delta u + H_{\psi v}\Delta v + H_{\psi w}\Delta w} \quad (13a)$$

$$\mathbf{\Delta\upsilon = H_{\upsilon u}\Delta u + H_{\upsilon v}\Delta v + H_{\upsilon w}\Delta w}$$

Where **H** matrices contain partial derivatives of the new variables with respect to the base variables, and because **u**, **v** and **w** are the variables that physically affect the process it must be possible to determine **u** and **v** from and measurable disturbances in **w**. thus means also the relationships.

$$\mathbf{\Delta u = M_{u\psi}\Delta\psi + M_{u\upsilon}\Delta\upsilon + M_{uw}\Delta w} \quad (14a)$$

$$\mathbf{\Delta v = M_{v\psi}\Delta\psi + M_{v\upsilon}\Delta\upsilon + M_{vw}\Delta w} \quad (14b)$$

Have to exist. Now the steady state model for the new control structure can be derived as follows: eliminating of from equations (13) by equation (10b) gives

$$\mathbf{\Delta\psi = \left(H_{\psi u} + H_{\psi v}G_{vu}\right)\Delta u + (H_{\psi w} + H_{\psi v}G_{vw})\Delta w} \quad (15a)$$

$$\mathbf{\Delta\upsilon = \left(H_{\upsilon u} + H_{\upsilon v}G_{vu}\right)\Delta u + \left(H_{\upsilon u} + H_{\upsilon v}G_{vw}\right)\Delta w} \quad (15b)$$

The primary manipulators have to be independent from each other even , this means that the transformations have tobe such that the matrix $\mathbf{(H_{\psi u} + H_{\psi v}G_{vu})}$ is non singular, also if the manipulators of the base structure are the variables that in reality affect the column it must be possible to determine **u** (and **v**) from , and measurable disturbance in **w**. because is a dependent variable, **u** must in principle be determinable from $\mathbf{\psi}$ and $\mathbf{w}$. This implies that **u** can be solved from equation (14a), giving

$$\mathbf{\Delta u = \left(H_{\psi u} + H_{\psi v}G_{vu}\right)^{-1} \cdot \left(\Delta\psi - \left(H_{\psi w} + H_{\psi v}G_{vw}\right)\Delta w\right)} \quad (16)$$

Elimination of from equations 10, and by equation (15b) then gives the model in equation (13a) where

$$\mathbf{G_{y\psi} = G_{yu}\left(H_{\psi u} + H_{\psi v}G_{vu}\right)^{-1}} \quad (17a)$$

$$\mathbf{G_{y\omega} = G_{yw} - G_{y\psi}\left(H_{\psi w} + H_{\psi v}G_{vw}\right)} \quad (17b)$$

$$\mathbf{G_{\upsilon\psi} = \left(H_{\upsilon u} + H_{\upsilon v}G_{vu}\right).\left(H_{\psi u} + H_{\psi v}G_{vu}\right)^{-1}} \quad (17c)$$

$$\mathbf{G_{\upsilon\omega} = \left(H_{\upsilon w} + H_{\upsilon v}G_{vw}\right) - G_{\upsilon\psi}\left(H_{\psi w} + H_{\psi v}G_{vw}\right)} \quad (17d)$$

Equations 17 provide the relationships between two arbitrary control schemes. And based on these equations we can deduce the model for any control structure knowing the model of the base structure (in our case the base model is the LV model [1],[3]) .

4. DYNAMIC RELATIVE MAGNITUDE CRITERION (DRMC)

The DRMC is a set of plots of magnitude/log frequency for its elements . The DRMC elements have been arranged into an array as diagonal and off-diagonal elements and interpreted as graphical representations, the diagonal elements are like the RGA,Relative Gain Array [12],[14] relate open loop and closed loop behavior of the fully controlled system.

4.11 The construction of DRMC elements

- ***The diagonal elements***

$$\delta_{ii}(s) = \frac{\left(\dfrac{y_i(s)}{u_i(s)}\right)_{all\ loops\ are\ open}}{\left(\dfrac{y_i(s)}{u_i(s)}\right)_{all\ loops\ are\ closed\ except\ loop\ i}} \tag{18}$$

- ***The Off- diagonal elements***

$$\delta_{ij}(s) = \frac{\left(\dfrac{y_i(s)}{u_{jsp}(s)}\right)_{i \neq j}}{\left(\dfrac{y_k(s)}{u_{ksp}(s)}\right)_{k\ is\ constant}} \tag{19}$$

4.2 Interpretation of DRMC elements [2]

The DRMC clearly expresses how the individual control loops respond to their own set-points through the diagonal elements and to other set points through the off-diagonal elements. From the definition of the criterion, the system interaction caused by the closed control loops, will be very weak for those pairs of variables with a relative magnitude of unity at loops resonant frequencies, as the magnitude of the diagonal elements of the DRMC between controlled variables yi and manipulated variables ui departs from unity, more interaction must be expected.The diagonal elements of the DRMC carry information about how a single loop will respond to changes in its own set point. However they don't supply any useful indication about the direction and magnitude of dynamic interaction with other loops.The off-diagonal elements $\boldsymbol{\delta}_{ji}$express how much the $\mathbf{J}^{th}$ loop is excited relative to the response of the $\mathbf{i}^{th}$ loop when a set point is made in the ith loop. The $\boldsymbol{\delta}_{ji}$ for the range of frequencies where a system works (i.e. the loop resonant frequencies) should be much smaller than unity for the rejection of true interaction or disturbance between loops.

5. THE ASSESSMENT OF INTERACTIONS IN THE LISTED CONTROL SCHEMES

Figures: (2),(3),(4), and (5) show the DRMC diagonal and off-diagonal elements for LV,DV and LB respectively, the resonance frequencies where the DRMC elements are computed are given in Table 1. The controllers' parameters (PI controllers) used in order to tune the loops are given in Table 2.

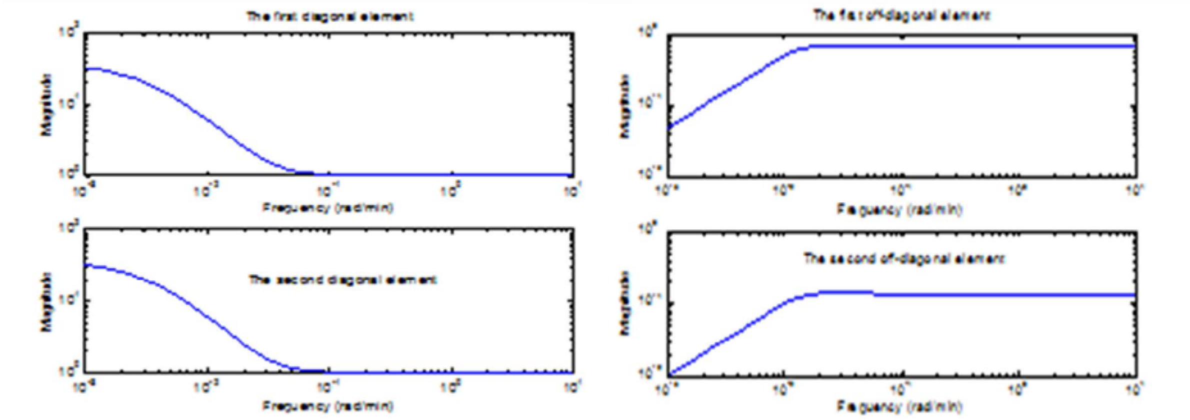
Table 1 .The frequencies where the system works

Control. Structure	ω_{r1} (rad/min)	ω_{r2} (rad/min)
(LV)	0.01	0.01
(DV)	0.01	0.01
(L/D V/B)	0.01	0.01
Ryskamp	0.01	0.01

Table 2.The controllers tuning for different configurations

Control structure	g_{c1}		g_{c2}	
	K_p	T_i	K_p	T_i
(LV)	4	41.3	-3	41.3
(DV)	-3.39	41.3	-217.8	41.3
(L/D V/B)	79.21	41.3	-65.01	41.3
Ryskamp's	-1.2	41.3	-166	41.3

- ***DRMC for LV control***



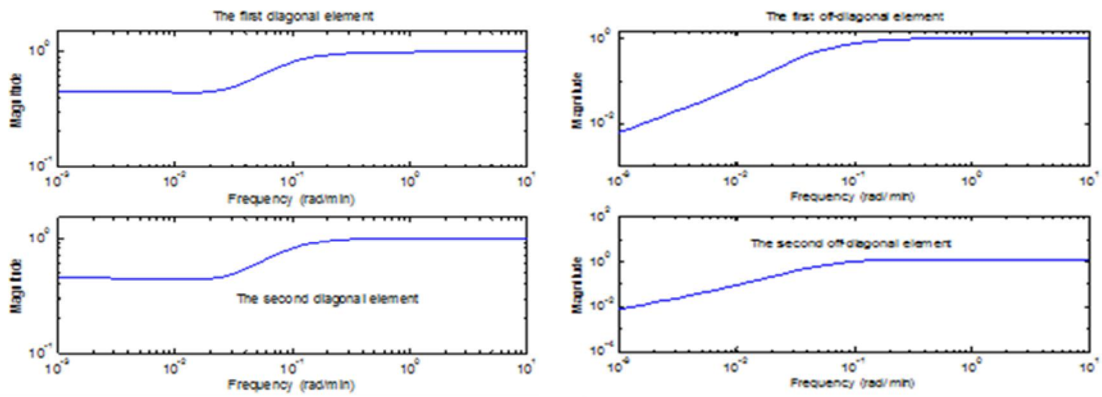
- ***scheme***

(a) Diagonal elements (b) Off-diagonal elements

Fig.2. DRMC Values for (LV) Configuration

As it is shown in Fig. (2.a), the magnitude of the diagonal elements for the range where the system works (i.e. the resonant frequency) are far from unity $\delta_{11} \approx \delta_{22}=7$ which means that strong interactions exist between the loops, the fact that let the (LV) configuration to be not recommended for two point control (i.e. where all loops are in automatic). Fig (2b) shows the off-diagonal elements $\delta_{12}=0.8$ and $\delta_{21}=1$ in the resonant frequencies which indicate that there exist large disturbances between the two loops and propagate approximately by the same magnitude

- ***DRMC for DV control scheme***

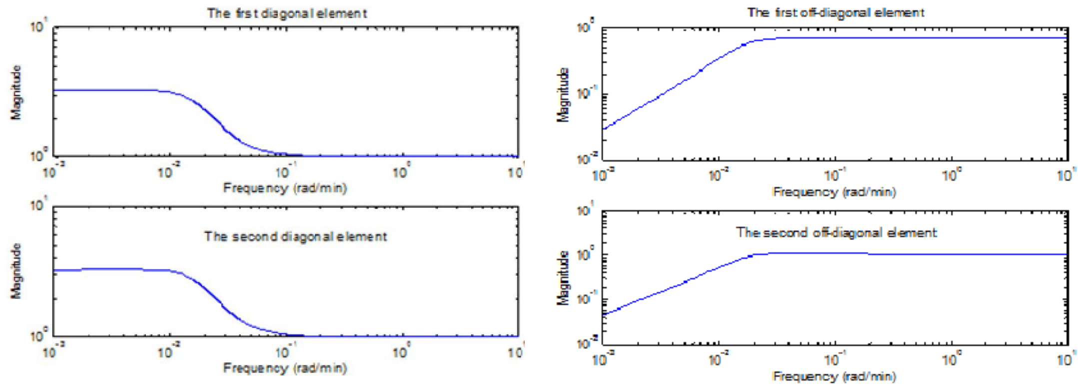


(a) Diagonal elements (b) Off-diagonal elements

Fig.3 DRMC Values for (DV) Configuration

The distillation column under this configuration is a non-interactive as it is indicated by the DRMC diagonal elements shown in Figs (3) (δ_{11}=0.1 and δ_22=0.4) are close to unity). For the off-diagonal elements we notice that (δ_{21}=0.1 and δ_{12}=0.09 i.e. $\delta_{21}>\delta_{12}$) which means that there exist disturbances that propagate from the top loop to the bottom loop. In general this configuration is a good choice in the sense of interactions but in reality there are problems that affect the operation of the column under this control scheme the major problem that may rise with this configuration is the effect of level control, such that with fast condenser level control, the increase in boil-up goes up the column, but is then returned back as a reflux through the action of the condenser level controller (since **D** is constant), and we have an increase in the internal flows only. Two other practical drawbacks for this configuration should be mentioned in first the performance may change depending on operating conditions, the second is Poor performance if failure leads to **D** constant (for example, if the top measurement fails[13]).

- ***DRMC for Ratios (L/D V/B) control scheme***

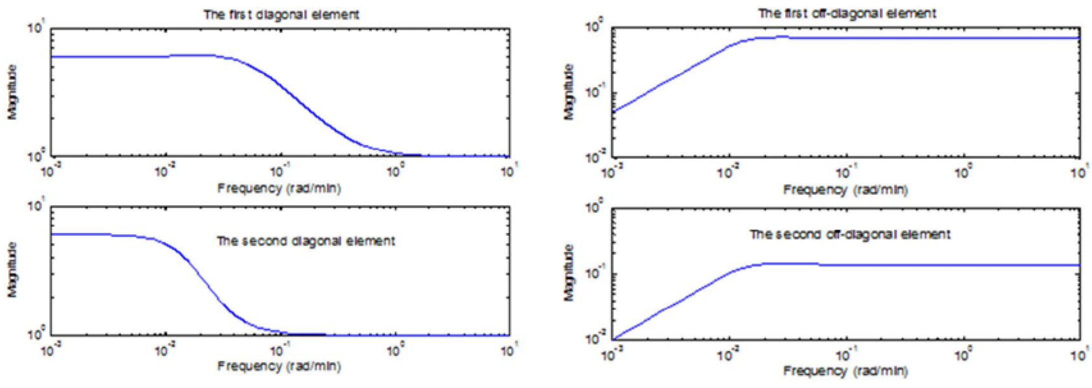


(a) Diagonal elements (b) Off-diagonal elements

Fig.4 DRMC Values for (L/D V/B) Configuration

The distillation column under this configuration is interactive as it is indicated by the diagonal elements of the DRMC shown in Fig 4a, (δ_{11}= δ_{22}=3.2) but compared with the energy balance configuration the degree of interactions is smaller (this also can be deduced using the RGA [15]). The examination of the off-diagonal elements (Fig 4b) shows that δ_{21}=0.6 is greater than δ_{12}=0.35 which indicates that there is disturbance propagation from the top loop to the bottom loop. The main disadvantages of this configuration is the need for measurements of all flows **L,D,B** and **V** which makes it more failure sensitive and more difficult to implement.

- ***DRMC for Ryskamp's control scheme***



(a) Diagonal elements (b) Off-diagonal elements

Fig.5 DRMC Values for Ryskamp's Configuration

The diagonal elements at the resonant frequencies shown in Fig (5a) are far from unity (δ_{11}= δ_{22}=5.5), but there values are small compared with those of **LV** control scheme, which indicates that the degree of interactions exist in this configuration is small compared with conventional control, this is according to decoupling (implicit) effect which results from the property that the scheme holds the reflux ratio constant if the top composition controller is constant. Fig (5b) shows the DRMC off-diagonal elements that indicate that there is a large disturbance propagation from the top loop to the bottom loop (sinceδ_{12}=0.6 >δ_{21}=0.35)

6. CONCLUSION

The choice of the best configuration for dynamic control of distillation column is a major concern, and considerable research activity has been devoted to finding the best control configuration. However some control configuration are characterized by their simple structure and others are complexes and they are developed to overcome the problems raised in the simple configuration taking into account the huge development in numerical methods field. In this paper we have considered four configurations and we compare them by the taking the existing of interactions as a tool of comparison ,the results show that the new complex ratios configuration give good results compared with the simple one it remains the fact these configurations are not simple to implement

Appendix

Column A: a particular high purity binary distillation column with 40 theoretical stages (39 trays and a reboiler) plus a total condenser.

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