Eco-efficiency of control configurations using Exergy

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***Abstract*— For general multi-input multi-output (MIMO) processes, thermodynamic properties like exergy have been previously used for the development of eco-efficiency analysis tools e.g. Relative Exergy Array (REA) [1, 2], and Exergy Eco-efficiency Factor (EEF) [3]. The REA is easy to use, compares several control scheme candidates for single units and ranks them according to their exergy interactions between control loops. The EEF provides means to determine the effect of a control scheme on the eco-efficiency of the whole process. In this paper, our intention is to justify the use of EEF and REA, compare EEF recommendations to REA, and consider EEF for the whole process eco-efficiency and discuss the similarities and differences between REA and EEF. Furthermore these results of testing REA and EEF on a realistic case study will be analysed to provide some practical recommendations on their usage.**

Keywords- Relative exergy array (REA); Control configurations; Exergy eco-efficiency factor (EEF); Eco-efficiency

I. Introduction

Most industrial chemical processes are multi-input multi-output (MIMO) in nature. These systems can be either controlled by a multivariable or centralized MIMO controller or by a set of single-input single-output (SISO) controllers. Since centralized multivariable controllers are complex and lack integrity, decentralized control systems have more attractive advantages: i) simple algorithms; ii) ease of understanding by plant operating personnel; and iii) standard control design developed for common unit operations [4]. Therefore, they are more often selected for control of MIMO systems.

For a decentralized type of control system, the control system structure decides the best control scheme. Control scheme selection pertains to the pairing of manipulated (MV) and controlled variables (CV). For a process or plant, control scheme selection is a straightforward task, provided that no interactions are present between the various control loops in multi-loop control schemes of that process or plant. However, this is rarely the case in process control design practice. A well performing control scheme selection is essential because the incorrect pairing of MV and CV will result in poor performance.

There are several techniques and methods for designing or selecting decentralized MIMO control schemes, such as the relative gain array (RGA), the Niederlinski index (NI), singular value decomposition (SVD), the condition number (CN) and Morari's resiliency index (MRI) [5-7].

In some cases, these steady state information based techniques (RGA, NI, SVD and CN) can lead to incorrect conclusions concerning the control scheme selection. Dynamic effects are also included in some techniques/methods to minimize the deficiency of these steady state techniques. For example, this happens in dynamic relative gain array (DRGA), internal model control (IMC) and effective relative gain array (ERGA). Using the steady state (RGA, NI, SVD and CN) and dynamic (DRGA, IMC and ERGA) techniques, well performing control schemes are further selected. The viability of a well performing/selected control scheme is further validated by the dynamic simulation of responses to the various process disturbances.

Steady state and dynamic techniques for selecting MIMO control schemes focus on controllability and control loop stability. Control system structure or control scheme selection is a large part of process control. In this age of ubiquitous industrialization and in the wake of decreasing energy resources, increasing energy costs and energy crises, special attention must be paid to the control system structure or control scheme selection, as a poorly structured control scheme can lose a great deal of energy from a process or plant. In the wake of energy crises, control scheme selection must also consider energy usage, cost and ecological impacts. This can be achieved by integrating control scheme selection and energy cost/energy usage/environmental impacts.

Thermodynamic properties such as exergy have the potential to amalgamate several elements into a single domain, these include; control system structure/control scheme selection and energy cost/energy usage/environmental impacts. The concept of exergy indicates what is wasted in terms of energy or the eco-efficiency of the process/plant. Exergy is the component of energy which is available for useful work. Kotas [8, pp 7] defines exergy as "The maximum amount of work/useful energy drawn from a process/material stream as it

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comes from its original state (process condition) to the ultimate dead state (reference state) during which it interacts only with the environment”. At the ultimate dead state, the process/material stream is in thermodynamic (thermal, mechanical and chemical) equilibrium with the environment [9].

The total energy of a material stream has two main parts (available energy and unavailable energy). Exergy of a material stream accounts for the quality of energy or available energy. According to the 1st law of thermodynamics energy in and out of a process is equal. According to the 2nd law of thermodynamics exergy in is greater than exergy out due to entropy generation or exergy destruction during the process. The fraction of non-available energy normally increases from input to output due to exergy destruction during a process. The increase in non-available energy is also called available energy loss as shown in Figure 2.

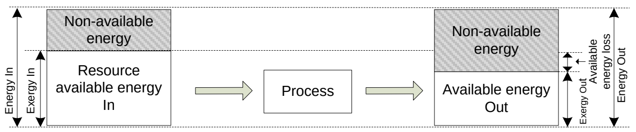

Figure 1. Energy and Exergy

Exergy accounts for the quality of energy/fraction of energy that can be fully converted into useful work and/or other types of energies. Every irreversible process causes exergy destruction leading to an increased exergy/energy requirement or entropy production. Since exergy can detect and evaluate the causes of the thermodynamic imperfections of the considered process/material stream, it can therefore be used as a measure to evaluate the eco-efficiency of the process.

Eco-efficiency is also a measure of progress in green chemical engineering growth. The concept of eco-efficiency can be traced back to the 1960s as the concept of environmental efficiency, or as a business when linked to sustainable development. Eco-efficiency has a role in expressing how efficient economic activity is with regard to nature’s goods/services. The concept of eco-efficiency focuses on methods of resource use, obtaining economic and environmental progress through efficient use of resources and lower pollution/emissions.

The World Business Council for Sustainable Development (WBCSD) states that eco-efficiency is achieved through the practice of producing "valuable goods and services that satisfy human needs and bring quality of life with reduced environmental impacts and resource intensity in line with the Earth's estimated carrying capacity." In other words eco-efficiency means producing more with less. An eco-efficient process is ecologically friendly and economically viable. Ecologically friendly practices signify a process with reduced consumption of energy/destroyed exergy. This diminution in energy utilization reduces the operational expenses of that process. Efficient use of energy/exergy plays an important role for sustainability and minimizing environmental impacts.

Exergy has many valuable uses in process design and control to facilitate these complex tasks. There are many exergy based tools and methods, such as; efficiency concepts, exergy flow diagrams, relative exergy array (REA) and exergy eco-efficiency factor (EEF). The REA is used to measure control scheme interactions and exegetic efficiency for the various possible MIMO control schemes [1, 2, 10]. However, the REA only measures the eco-efficiency within the scope of single, decentralized control loops. To overcome this deficiency in REA, the EEF is defined and employed for the eco-efficiency analysis of the whole process [3]. More details of REA and EEF are presented in section II.

In this work, the intention is to justify the use of REA and EEF coupled with classical controllability tools (RGA, NI, SVD and CN), compare EEF recommendations to REA, and consider EEF for the whole process eco-efficiency and discuss the similarities and differences between REA and EEF. The results of REA and EEF are also analyzed to provide some practical recommendations on their usage.

This article is further organized as follows. After this general and brief introduction related to this research, more details of REA and EEF are discussed and explained. Following this, the results of REA and EEF are explained with a realistic case study. Finally, the results are discussed and conclusions drawn.

II. RELATIVE EXERGY ARRAY (REA) AND EXERGY ECO-EFFICIENCY FACTOR (EEF)

Relative gain is defined as “The ratio of open loop process gain in an isolated loop to apparent process gain in the same loop when all other control loops are closed and are in perfect control”, [11]. RGA is a matrix composed of elements defined as the ratio of open-loop to closed-loop gains. One of its elements, relative gain, λ_{ij}, which relates the j^{th} input u_j and the i^{th} output y_i, can be expressed by the following Equation (1).

$$\lambda_{ij} = \frac{\left(\dfrac{\Delta y_i}{\Delta u_j}\right)_{all-loops-open}}{\left(\dfrac{\Delta y_i}{\Delta u_j}\right)_{all-loops-closed(in-perfect-control)-except-u_j-loop}} \qquad (1)$$

A. Relative exergy array (REA)

Exergy helps to develop many tools for the facilitation of process design and control, such as exergetic efficiency, REA and EEF.

For the understanding of Relative Exergy Array (REA), the concept of exergetic efficiency is introduced. Exergetic efficiency is defined as the ratio of the exergy out to the exergy in to a process as shown in Equation (2). A general process for exergetic efficiency calculation is shown in Figure 2.

Figure 2. A general control loop portion

$$\eta = \frac{B^{\bullet}_{Out}}{B^{\bullet}_{In}} \qquad (2)$$

where η = Exergetic efficiency, $B^{\bullet}_{Out}$ = Total exergy going out of a process and $B^{\bullet}_{In}$ = Total exergy coming in to a process.

In a control loop a manipulated variable (MV) is paired with a controlled variable (CV) and both are linked with each other by some process as shown in Figure 2. In a control loop, the exergy of the manipulated variable (u_j) stream is the total exergy coming in to the process ($B^{\bullet}_{In}$) and the exergy of the control variable (y_i) stream is the total exergy going out of a process ($B^{\bullet}_{Out}$) as shown in Figure 2. The ratio of the exergy of the control variable stream to the exergy of the manipulated variable stream gives the exergetic efficiency.

The Initial exergetic efficiency is based on the exergy of the manipulated variable stream and the exergy of the control variable stream before a step input in the exergy of the manipulated variable stream. The exergy gain ratio is calculated after a step change in the exergy of the manipulated variable stream. The exergy gain ratio defined by Equation (3) gives the exergetic efficiency of the process.

$$\tau_{ij} = \frac{\Delta B(y_i)}{\Delta B(u_j)} = \frac{B^{\bullet}_{Out,Final} - B^{\bullet}_{Out,Initial}}{B^{\bullet}_{In,Final} - B^{\bullet}_{In,Initial}} \qquad (3)$$

where τ_{ij} = Exergy gain ratio

Equation 3 is also called the generic exergy gain ratio which allows an alternate measurement of exergetic efficiency, defined by Equation 2. The open loop exergy gain of a control loop can be calculated via Equation 3 when all other loops are open. The open loop exergy gain is analogous to the open loop gain in the Relative Gain Array (RGA) as shown in Equation 4.

$$k_{ij} = \frac{\Delta y_i}{\Delta u_j} = \frac{y_{i,Final} - y_{i,Initial}}{u_{j,Final} - u_{j,Initial}} \qquad (4)$$

where k_{ij} = simple gain ratio

In the open loop gain ratio calculation, all loops are open and no interactions from other loops affect the considered loop (u_j - y_i). When all other loops except (u_j - y_i) are closed then loop interactions from other loops affect the considered loop (u_j - y_i). These loop interactions change the effect of manipulated variable stream step input to the controlled variable stream of control loop (u_j - y_i) in terms of control variable y_i and its exergy. So a great variation in open loop gain or open loop exergy gain to closed loop gain or closed loop exergy gain, accounts for large interactions within the control loops. This translates to an alternate measure of loop interactions by using exergy values. With loop interaction measurement it also accounts for exergetic efficiency of a control loop (u_j - y_i) effected by interaction from other loops.

So from the above discussion relative exergy gain is defined by Equation 5, (analogous to relative gain in RGA as shown in Equation 1).

$$\gamma_{ij} = \frac{\left(\dfrac{\Delta B_{total}(y_i)}{\Delta B_{total}(u_j)}\right)_{\text{all loops open}}}{\left(\dfrac{\Delta B_{total}(y_i)}{\Delta B_{total}(u_j)}\right)_{\text{all loops closed (in perfect control) except } u_j \text{ loop}}} \qquad (5)$$

where γ_{ij} = Relative exergy gain ratio

For all pairing combinations in multi-loop SISO control, relative gains (λ_{ij}) are calculated. These relative gains are arranged into an array called RGA (Λ) as shown by Equation 6. Similarly for all pairing combinations in multi-loop SISO control, relative exergy gains (γ_{ij}) are calculated. These relative exergy gains are arranged into an array called REA (Γ) as shown by Equation 7. The interpretations of RGA and REA values are given by [6, 12].

$$\Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \cdots & \lambda_{1n} \\ \lambda_{21} & \lambda_{22} & \cdots & \lambda_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \lambda_{n1} & \lambda_{n2} & \cdots & \lambda_{nn} \end{bmatrix} \qquad (6)$$

$$\Gamma = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1n} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \gamma_{n1} & \gamma_{n2} & \cdots & \gamma_{nn} \end{bmatrix} \qquad (7)$$

where Λ = Relative gain array (RGA) and Γ = Relative exergy gain array (REA)

The definition of the REA implies that the system or process under consideration is linear so that the gains calculated are valid for the full range of operation of the control structure. In the case of non-linear systems or processes the results for the REA have to be recalculated for each range of the process where the linear assumption holds.

The REA can be used mainly as a screening tool for candidate control structures, but for a complete detailed analysis of the control structure performance, a detailed dynamic simulation is recommended.

B. Exergy eco-efficiency factor (EEF)

Exergy eco-efficiency factor (EEF) is based on an understanding of the total exergy of each material stream in and out of the thermodynamic process as shown in Figure 2. The ratio, Equation (2) is the exergetic efficiency of this process (Figure 2) which is a measure of eco-efficiency. This general process is a portion of the control loop between the manipulated and the control variables. However it does not provide any information about how the control loop configuration affects this exergetic efficiency. EEF connects the control loop configuration to the eco-efficiency. The exergy eco-efficiency factor for a control pair (u_j, y_i), is defined as,

$$\tau_{ij} = (\Delta B_{out} - \Delta B_{in}) \frac{\Delta u_j}{\Delta y_i} \quad (8)$$

where Δu_j denotes a step change of the *MV* u_j, Δy_i denotes a response in the *CV*, y_i, caused by a step change of u_j, and ΔB_{out} and ΔB_{in} represent the exergy differences caused by the *MV* step change for exergy out and exergy in, respectively. For example, if $\tau_{21}$is less than τ_{22}, it means that for the same amount of *CV* change Δy_2, using u_1, will cause less exergy destruction than using u_2. The final interpretation is that the control pairing (u_1, y_2) is more eco-efficient than the pairing (u_2, y_2).

The EEF shows how much exergy will be destroyed by using different *MV* to control the same amount of *CV* change. It can provide a quantitative measurement of the exergy consumption. By comparing the sum of EEF of one control configuration with another, the approximate amount of exergy to be saved can be obtained. This will be very useful in some situations, for example, when control configuration A makes an exergy saving of 10%, compared to control configuration B, the implementation of control configuration B is more expensive than it is for control configuration A, Thus, on this basis, control configuration A may be selected.

For a 2 x 2 example, if τ_{21} is less than τ_{22}, it means that for the same amount of *CV* change, Δy_2 using *MV* u_1, will cause less exergy change/loss than will using *MV* u_2. The final interpretation is that control pair (u_1, y_2) is more eco-efficient than pair (u_2, y_2).

EEF helps engineers to build an eco-efficient process which is ecological friendly and economically viable. Since exergy accounts for the quality of energy, thus it can be used as a measure to evaluate the eco-efficiency for a process design. A process is called eco-efficient if it uses a relatively small amount of energy or the destruction of exergy is low.

Control loop configurations can be determined by techniques such as RGA, NI and SVD, it is usual that several candidate control loop configurations can be implemented. In regard to eco-efficiency, the EEF can be used to select the best control loop configuration from among the candidates in the sense of eco-efficiency.

EEF calculation for different cases with all possible control schemes is difficult. It increases the computational load on process design engineers. The development of an algorithm/software package for EEF calculation has been done, which combines together a commercial simulator, VMGSim and Excel to calculate the EEF. A potential help is obtainable in EEF calculation by using a commercial simulator VMGSim [13].

C. *Validation of EEF Results*

Dynamic simulation is the best way to validate the proposed eco-efficiency factor. By recording the exergy consumptions of several control configurations, the most eco-efficient control configuration can be identified and dynamic results compared to the results from the eco-efficiency factor.

Dynamic exergy versus time can be approximated by several exergy calculations at different conditions during the dynamic response of a process. The exergy values of the process dynamic response at different time intervals are calculated. As chemical simulators still do not have the ability to directly calculate and display the total exergy of a material stream, these simulators cannot automatically calculate exergy versus time at every point. Simulators such as the HYSYS and the VMGSim can only calculate steady state exergy values at given process conditions. For dynamic exergy versus time, different process condition points are selected during the process dynamic response due to step input disturbances. The selection of calculation points depends on the dynamic response of the process. In order to get the maximum information in regard to dynamic response, if the variation in the process conditions with time is large, then the time interval between the selected points is decreased. With less variation in the process conditions, the time interval between the selected points is increased. Then the exergy values are calculated on these selected points during the dynamic process response. Exergy values at different points are calculated with the procedure developed in [14]. Then those exergy points are used to approximate the dynamic exergy response versus time.

III. CASE STUDY

A. *Process description*

A monochlorobenzene (MCB) separation process is selected for this case study, and is used to show how the REA and EEF provides information regarding the best control loop configuration among the candidates in the sense of eco-efficiency. MCB plant consists of three main units: a flash vessel (F1), an absorption column (T1) and a distillation column (T2), as shown in Figure **3**. VMGSim (process simulator) with the NRTL activity thermodynamic model was used for the simulation of the MCB separation process. The detailed information regarding feed conditions and column specification can be found in [15].

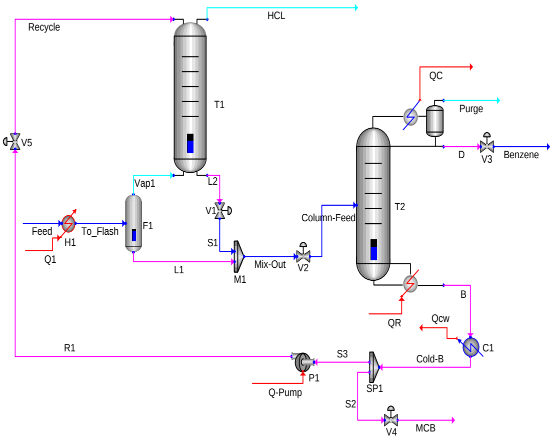

Figure 3. MCB separation process schematic

For comparison, three basic control configurations can be defined for the dual composition control of the distillation column (T2) and composition of HCl (x_{HCl}) leaving in the vapour stream of the absorber, namely LVQ_{cw}, LBQ_{cw} and DVQ_{cw}. Each configuration is comprised of three main composition control loops (name of each configuration). For example, in the LVQ_{cw} control configuration, L *(Reflux rate)* is used to control the composition of the top product (x_D), boil-up rate (V) is used to control the composition of the bottom product (x_B), and cooler duty (Q_{cw}) is used to control the composition of vapour stream leaving the absorber (x_{HCl}). It behaves as a pseudo 3 x 3 system because; i) three inventory control loops of distillation column and other control loops of MCB plant are assumed to be under perfect control; and ii) Control loops other than the composition control are not interacting with the composition loops, therefore are not included in the analysis.

B. *Results and Discussion*

The simulation model shown in Figure 3 was used to do the required step tests. Step tests are performed to obtain the necessary information to calculate the RGA, DRGA, REA, NI and CN as shown in Table 1.

The LVQ_{cw} and DVQ_{cw} control configurations are further selected based on classical controllability tools (RGA, NI, SVD and CN) results, to ascertain the most eco-efficient control configuration (LVQ_{cw} or DVQ_{cw}) by using the REA and EEF.

The REA results, as shown in Table 1, depict that all three control configurations (LVQ_{cw}, LBQ_{cw} and DVQ_{cw}) have exergy interactions and the thermodynamic (exergetic) efficiencies of the control loops are affected by these exergy interactions. For the LVQ_{cw} configuration, the REA results show that the exergy changes for open loop are smaller and opposite in direction to the exergy changes caused by loop interactions. For the LBQ_{cw} control configuration, the REA results show that exergy changes due to loop interactions are almost equal and larger than the exergy changes due to the open loop operation. For the DVQ_{cw} control configuration, the REA results show that exergy changes for open loop operation are much smaller and are in the same direction as the exergy changes caused in closed loop operation, except for one element.

Table 1. RGA, DRGA, REA, NI and CN results for the whole MCB plant

Configurations	RGA	DRGA	REA	NI	CN
LVQ_{cw}	$\begin{bmatrix} 6.30 & -4.76 & -0.54 \\ -5.80 & 6.50 & 0.35 \\ 0.52 & -0.70 & 1.20 \end{bmatrix}$	$\begin{bmatrix} 3.80 & -2.80 & 0.02 \\ -1.40 & 2.60 & -0.23 \\ -1.40 & 1.20 & 1.20 \end{bmatrix}$	$\begin{bmatrix} 0.006 & -0.25 & 1.25 \\ 1.21 & -0.23 & 0.02 \\ -0.21 & 1.48 & -0.27 \end{bmatrix}$	1.15	31
LBQ_{cw}	$\begin{bmatrix} 0.88 & 0.10 & 0.02 \\ 0.12 & 0.92 & -0.05 \\ 0.00 & -0.03 & 1.02 \end{bmatrix}$	$\begin{bmatrix} 0.84 & -1.60 & 1.76 \\ 0.18 & 0.38 & 0.43 \\ -0.03 & 2.20 & -1.19 \end{bmatrix}$	$\begin{bmatrix} 0.88 & 0.13 & -0.007 \\ 0.12 & 0.61 & 0.26 \\ -0.002 & 0.26 & 0.74 \end{bmatrix}$	-1.0	16
DVQ_{cw}	$\begin{bmatrix} 0.52 & 0.49 & -0.01 \\ 0.39 & 0.51 & 0.10 \\ 0.10 & 0.00 & 0.91 \end{bmatrix}$	$\begin{bmatrix} 0.91 & 0.03 & 0.06 \\ 0.03 & 1.02 & -0.05 \\ 0.06 & -0.05 & 0.99 \end{bmatrix}$	$\begin{bmatrix} 0.11 & 0.85 & 0.03 \\ 0.83 & 0.14 & 0.03 \\ 0.05 & 0.006 & 0.94 \end{bmatrix}$	0.97	23

According to the guidelines for interpreting the REA results, an element in REA close to the value of 1.0 indicates that thermodynamic (exergetic) efficiency and exergy changes of the control loop are not affected by other loops. The REA results, as shown in Table 1, show that leading diagonal elements of only the LBQ_{cw} control configuration are close to the value of 1.0 and that this would be a good candidate for selection because its thermodynamic (exergetic) efficiency and exergy changes are not affected by loop interactions.

The interpretation of the RGA, DRGA, NI, CN and REA results depict that a trade-off exists in this process between controllability, thermodynamic (exergetic) efficiency and exergy changes. The LBQ_{cw} control configuration is the best choice for selection, from the thermodynamic (exergetic) efficiency and exergy changes points of view, but it is the worst from the controllability point of view. When the results of the classical controllability techniques (RGA, DRGA, NI and CN) and REA contradict each other (as in this case), then dynamic simulation for validation is required

As it is affected by control loop interactions, the REA provides a means for the analysis of the thermodynamic (exergetic) efficiency and exergy changes of a control loop. The REA does not provide any information concerning the eco-efficiency analysis of the whole process or plant.

Table 2. EEFs for MCB plant

Control pairs	(L, x_D)	(D, x_D)	(V, x_B)	(B, x_B)	(Q_{cw}, x_{HCl})
EEF (kW. kgmole/h) or (kW)	94.3	3.41	78.72	1.08 E3	1.28 E4

The EEF was proposed for the eco-efficiency analysis of the whole process or plant. The EEF was developed to minimize the limitations of the REA e.g. the REA measures eco-efficiency solely within the scope of control loops. The EEF determines the eco-efficiency of the whole plant because its calculation is based on the total exergy destroyed in a process, total exergy coming in and going out of a process. A higher EEF value indicates that selection of that control configuration will result in higher exergy destruction, and vice versa. As the EEF provides the means to determine the true eco-efficiency of the whole plant, EEF analysis is preferred over REA analysis.

There are some similarities and differences between the EEF and REA. For example: the EEF is affected by the recycling of materials and energy streams like REA [10, 16]; and unlike the REA, the EEF considers a single possible control scheme at a time for analysis [3].

EEF results for whole MCB plant, as shown in Table 2, indicate that the control pair (Q_{cw}, x_{HCl}) will use the most exergy and be the least eco-efficient control pair, and the control pair (D, x_D) is the most eco-efficient control pair. Since both control configurations (LVQ_{cw} and DVQ_{cw}) include the same control pairs ($V - x_B$, $Q_{cw} - x_{HCl}$), we only need to compare the EEF for control pairs (L, x_D) and (D, x_D). For controlling x_D if we use D, it will make an exergy saving ≈ 2.0 % compared to use of L. Dynamic simulation procedure explained in section II.C is used to validate the steady state EEF results.

IV. Conclusions

The REA integrates concepts of process control and thermodynamic efficiency (exergetic efficiency). The REA provides a means to analyze the exergetic efficiency of a control structure as it is affected by control structure loop interactions. The EEF is employed for eco-efficiency analysis of the whole process, to overcome the deficiencies in REA. The EEF facilitates in the deciding of controllable and eco-efficient control schemes for the whole process. As the EEF provides the means to determine the true eco-efficiency of the whole plant, EEF analysis is preferred over REA analysis.

The LVQ_{cw} and DVQ_{cw} control configurations were selected based on classical controllability techniques. Both the LVQ_{cw} and the DVQ_{cw} control configurations are equally controllable, but the DVQ_{cw} control configuration is preferred over the LVQ_{cw} because it causes less exergy destruction (eco-efficient) than the LVQ_{cw} control configuration.

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