Fault Tolerant Control of the (^{13}C) Isotope Separation Cascade

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Abstract — *The(^{13}C) isotope separation cascade – from control engineering point of view – is a multivariable, distributed, nonlinear system, with strong interactions between the subsystems. Being a complex chemical plant, a robust, fault tolerant control is needed. The present paper discusses the idea to re-distribute the control task among the subsystems, imposing new set-points for each subsystem by local information exchange when a fault occurs. In order to ensure robustness, in the present work fractional order PI controllers are used, having one more degree of freedom in comparison with the classical, integer order PI controllers. The advantages of the method are illustrated by simulation results presenting different real fault scenarios.*

1 Introduction

Fault tolerant control represents a popular field of research, especially when it comes to dealing with faults that may occur in the functioning of the nuclear and avionics industries, chemical or petrochemical plants, etc. The usual method employed in this regard is based on hardware or analytical redundancy. Usually, hardware redundancy is preferred whenever dealing with high risk systems, such as airplanes or nuclear plants, to counteract a possible failure in these systems that could potential threaten the integrity or safety of people. Nevertheless, hardware redundancy comes with a major disadvantage, in terms of its high costs, which is why in other industrial processes, this type of solution is rarely used or even non-existent. In such cases, the hardware redundancy is limited to the use of redundant sensors, since these are usually much easier and less expensive than actuators. However, even though such a solution eliminates some of the failure problems, in the case of a major actuator failure, it would be impossible to keep the damaged system operating with an acceptable level of performance. A major concern then is to drive the system towards an optimal operating order, taking into account the desirable closed loop performance, as well as the degree of priority. In such cases, the main concern of the fault tolerant system is to minimize productivity losses (lower quality production), while at the same time to ensure a safe operation without danger to human operators or equipment. This solution offers the possibility for the system to continue its operation with decreased performance as long as it remains within acceptable limits.

The topic of fault-tolerance has attracted the interest of many researchers worldwide. Paper [1] employs linear matrix inequality (LMI) based optimization algorithm to develop a method for designing fault-tolerant state feedback controller with mixed actuator failures for power systems subject to random changes. In [2] is developed an adaptive control scheme for position and velocity tracking control of high speed trains under uncertain system nonlinearities and actuator failures, integrating neural networks with self-structuring capabilities. Paper [3] presents an open-circuit fault detection method for a grid-connected neutral-point clamped (NPC) inverter system. In [4] is proposed a reliable fault-tolerant model predictive control applied to drinking water transport networks.

Ever since the generalization of the PID controller, using any real order instead of integer order, was introduced by Podlubny [5], fractional order control has proven to be a robust viable solution for a large variety of processes. The broad range of applications ranges from slow to fast, from linear to nonlinear processes. For example, in [6] a robust positioning controller, build upon differintegral fractional operators, is designed for quadrotors, while in [7] a fractional order control scheme for the stabilization of the nonlinear chaotic Genesio-Tesi systems is proposed. Special software toolboxes and program suites for solving problems of fractional-order system identification, modeling, simulation, and control [8] are available. The authors also applied with success fractional order calculus [9, 10, 11].

This paper proposes to combine the advantages of fault-tolerant and fractional order control with application to a complex chemical process, the (^{13}C) isotope separation cascade, consisting in three interconnected subsystems. The occurrence of faults in some of these subsystems does not only affect the behavior of the faulty subsystem, but also the function of the overall system. The standard way to make such systems fault-tolerant is to diagnose the fault and to adapt the controller of the faulty subsystem to the current fault in order to restore the ability of the faulty subsystem to satisfy its control aim. In this research, the authors propose an alternative way: the interconnected subsystems have to fulfill their common task collectively rather than individually. In case of a fault in a subsystem, the overall control task is re-distributed among the faulty and the non-faulty subsystems in order to enable the overall system to satisfy its global goal in spite of the fault, or at least to minimize the loss in productivity and operate safe.

The structure of the paper is the following. After this short introductory part, Section 2 presents the case study, the (^{13}C) isotope separation cascade. In Section 3 the proposed control strategy is discussed, while Section 4 highlights the simulation results. The work ends with concluding remarks.

2 The (^{13}C) isotope separation cascade

The case study considered in this paper is the (^{13}C) cryogenic isotope separation process, occurring in a train of three interconnected distillation columns. The experimental unit is currently available at NIRDIMT – Cluj-Napoca, Romania, and enriches the concentration of the (^{13}C) isotope through the cryogenic distillation of pure carbon monoxide (CO).

This is a very difficult process, mainly due to the extremely small differences in the nuclear properties of the isotopes to be separated: (^{12}C) and (^{13}C). The natural concentration of the (^{13}C) isotope is about 1.1% and needs to be substantially increased, in order to be used as a tracer in various industries. A simple cryogenic distillation column, such as the one built at NIRDIMT of 7m length and 16mm diameter, can only offer an enrichment in (^{13}C) up to (8-10) at.% [12, 13] due to physical limitations. The final concentration can be raised by increasing the length of one column or by using a cascade of such separation columns of different diameters, as indicated in Figure1.

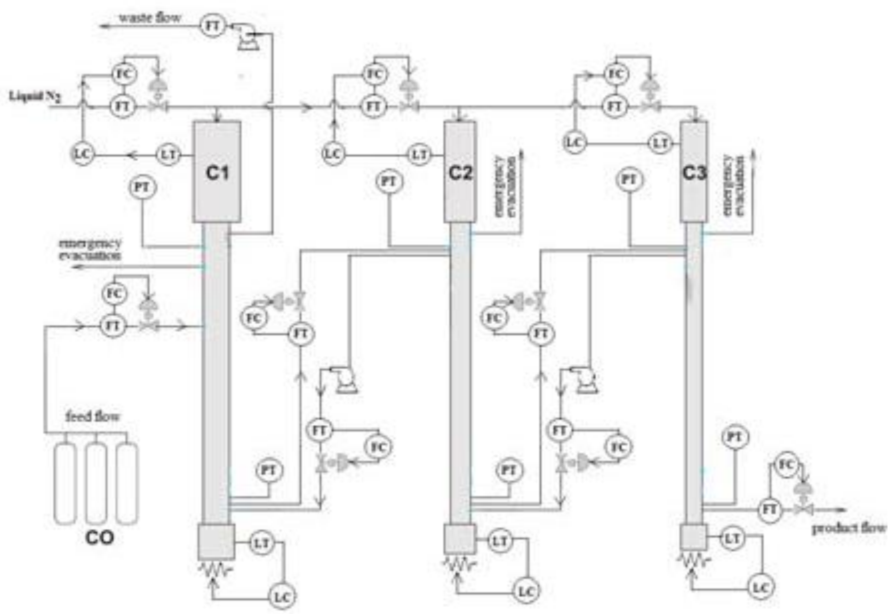


Figure 1. Schematic of the isotopic separation column cascade

Each column in the cascade presented in Figure 1 is composed of some main components: the actual body of the column, the condenser at the top, the boiler at the bottom and the vacuum jacket, necessary to insulate the column, as it operates at very low temperatures. As far as condenser is concerned, a cheaper and simpler solution is to use a common condenser for all three columns cooled with liquid nitrogen. The principle of separation is based on the common distillation process, with a gaseous upstream flow and a liquid downstream flowing through each of the columns. The gaseous upstream is generated by boiling the liquid carbon monoxide at the bottom of each column, while the liquid downstream flow is produced by condensing the carbon monoxide vapours at the top of each column. The working temperature is around -190^{o}C, since at this temperature, both the liquid and gaseous phase of (CO) co-exist [14]. Because of its lower boiling point, the (^{13}C) isotope will be accumulated in the bottom of each column. The final product, with an increased concentration of the (^{13}C) will be extracted from the bottom of the third column, as indicated in Figure 1.
To efficiently control the operation of this cascade, seven transducers are used to measure the feed flows, waste flows, products flows and the circulated and re-circulated flows between columns. Additionally, three sensors have been installed to measure the top

pressure in each column, while other three transducers are used to monitor the differential pressure between top and bottom of each column. For temperature measurements in the boiler of each column, three thermocouples are used, as well as three level transducers to measure the liquid carbon monoxide in each of the three boilers. Three pumps are also used to ensure the flows between the columns. For measuring the liquid nitrogen level in the common condenser, a special transducer has been installed [15].

3 The control strategy

The model of the (^{13}C) isotope separation columns cascade, linearized around its equilibrium point and scaled in a [-100%,+100%] range, has been determined previously [15]. The dynamics of the three columns presents similar dynamics and therefore may be described by similar mathematical models. The model of the first column is described by the transfer function matrix [15]:

$$\begin{pmatrix} p_{t1} \\ h_{CO1} \\ p_{b1} \end{pmatrix} = \begin{pmatrix} \frac{-0.1111}{s^2 + 1.094\,s + 0.08423} e^{-10s} & \frac{0.1152}{s^2 + 1.211\,s + 0.2021} e^{-32s} & 0 \\ \frac{-0.001731}{s^2 + 0.1343\,s + 0.001961} e^{-10s} & \frac{0.003846}{s^2 + 0.1547\,s + 0.004357} e^{-8s} & \frac{-1.104}{s + 0.1176} \\ \frac{-0.009918}{s^2 + 1.056\,s + 0.07036} e^{-18s} & \frac{0.006288}{s^2 + 1.085\,s + 0.09851} e^{-35s} & \frac{8.457}{s + 0.9851} \end{pmatrix} \begin{pmatrix} W_1 \\ F_1 \\ P_{el1} \end{pmatrix} \tag{1}$$

where p_{t1} is the top pressure, $p_{b1}$is the bottom pressure and h_{CO1} is the liquid CO level in the first column, W_1 is the waste flow from the first column, $F_1$is the feed flow to the first column and P_{el1} is the electrical power supplied to the boiler of the first column. The models for the second and third columns are described by the transfer function matrices [15]:

$$\begin{pmatrix} p_{t2} \\ h_{CO2} \\ p_{b2} \end{pmatrix} = \begin{pmatrix} \frac{-0.1111}{s^2 + 1.111\,s + 0.1011} e^{-8s} & \frac{0.1152}{s^2 + 1.311\,s + 0.3033} e^{-30s} & 0 \\ \frac{-0.001731}{s^2 + 0.13\,s + 0.0022} e^{-8.5s} & \frac{0.003846}{s^2 + 0.15\,s + 0.0044} e^{-7s} & \frac{-1.104}{s + 0.12} \\ \frac{-0.009918}{s^2 + 1.06\,s + 0.0784} e^{-16s} & \frac{0.006288}{s^2 + 1.105\,s + 0.1225} e^{-30s} & \frac{8.457}{s + 0.98} \end{pmatrix} \begin{pmatrix} W_2 \\ F_2 \\ P_{el2} \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} p_{t3} \\ h_{CO3} \\ p_{b3} \end{pmatrix} = \begin{pmatrix} \frac{-0.1111}{s^2 + 1.131\,s + 0.1213} e^{-7s} & \frac{0.1152}{s^2 + 1.361\,s + 0.3538} e^{-24s} & 0 \\ \frac{-0.001731}{s^2 + 0.145\,s + 0.003} e^{-6s} & \frac{0.003846}{s^2 + 0.17\,s + 0.006} e^{-5s} & \frac{-1.104}{s + 0.14} \\ \frac{-0.009918}{s^2 + 1.085\,s + 0.0985} e^{-13s} & \frac{0.006288}{s^2 + 1.12\,s + 0.133} e^{-27s} & \frac{8.457}{s + 0.985} \end{pmatrix} \begin{pmatrix} W_3 \\ F_3 \\ P_{el3} \end{pmatrix} \tag{3}$$

where the same notations have been used as in (1). The interactions between the columns are modeled as first order transfer functions [15]:

$$\begin{aligned}
&h_{CO1}(s) = \frac{1}{10s+1} W_2(s),\, h_{CO1}(s) = \frac{-1}{10s+1} F_2(s) \\
&h_{CO2}(s) = \frac{1}{10s+1} W_3(s),\, h_{CO2}(s) = \frac{-1}{7.5s+1} F_3(s) \\
&h_{CO3}(s) = \frac{-1}{6s+1} P_3(s)
\end{aligned} \tag{4}$$

where P_3 is the product flow from the third column.

The proposed process control assumes a decentralized approach, with the input-output pairing selected based on the Relative Gain Array (RGA). For each selected input-output pair a fractional order PI controller is designed, having the transfer function:

$$C(s) = K_p + K_i s^{-\lambda} \tag{5}$$

The controller parameters are established based on the equations corresponding to the performances indicated by [16]:

- gain crossover frequency:

$$\left|C(j\omega_{gc}) \cdot P(j\omega_{gc})\right| = 0\text{dB} \tag{6}$$

- phase margin:

$$\angle\left(C(j\omega_{gc}) \cdot P(j\omega_{gc})\right) = -\pi + \varphi_m \tag{7}$$

- and robustness to gain variations, imposed as flat phase evolution around the gain crossover frequency:

$$\left.\frac{d}{d\omega}\angle\left(C(j\omega)\cdot P(j\omega)\right)\right|_{\omega=\omega_{cg}} = 0 \tag{8}$$

where with *P* is noted the selected input-output pair from the whole system.

The performance specifications for the first input-output loop refer to a gain crossover frequency ω_{gc11}=0.03 rad/s, aphase margin $\varphi_{m11}=60^o$ and the flat phase evolution around the gain crossover frequency. Using theequations described in [17] the controller parameters are obtained as:K_{p11}= 0.4284, K_{i11}= 0.0263 andλ_{11}=1.2339. For the second input-output loop and for gain crossover frequencyω_{gc12}=0.03 rad/s, aphase margin $\varphi_{m12}=60^o$ and the flat phase evolution around the gain crossover frequency, the parameters are K_{p12}= 1.5039, K_{i12}= 0.0095 and λ_{12}=1.2746. For the third input-output loop and for gain crossover frequency ω_{gc13}=1.8 rad/s, a phase margin $\varphi_{m13}=66^o$ and the flat phase evolution around the gain crossover frequency, the following parameters are obtained K_{p13}= 0.1341, K_{i13}= 2.5309 and λ_{13}=0.9575. Applying the same procedure for the second and third columns, the fractional order controllers for these two subsystems are obtained. To implement the controllers, the Oustaloup RecursiveApproximation method is used [18].

With these fractional order controllers the robustness to gain variations is guaranteed, but the complex and dangerous character of the process makes necessary to ensure also fault tolerance. In Figure 2 is presented the fault tolerant control structure adopted in the present paper. The isotope separation columns (the three subsystems S1, S2 and S3) are physically coupled, with strong interconnection between each unit. In each subsystem the top pressure, bottom pressure, liquid CO level in the boiler, electrical power supplied to the boiler are controlled by the decentralized fractional order controllers C1i, C2i and C3i designed earlier, with i=1,2,3. In the fault-free case the set-points ref1i, ref2i and ref3i are such that the overall goal is reached. If a fault occurs, e.g. in S1, the diagnostic unit D1 detects, isolates and identifies this fault and provides this information to the reconfiguration unit R1. Then this reconfiguration unit R1 generates new set-points ref1in, ref2in, ref3in that are consistent with the global control goal and with the constraints that are imposed on the subsystem S1 by the fault. The generated (new) set-points are sent to the controllers C2i and C3i over the communication network. As a result, the overall system reaches the overall goal, or the most appropriate value, which can be acquired in the presence of fault.

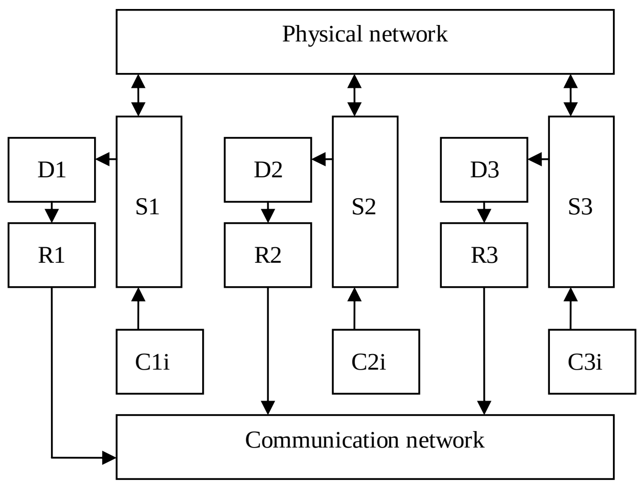


Figure 2. Block scheme of the proposed control structure

4 Simulation results

In order to validate the proposed fault tolerant robust control structure a series of simulations were carried out inspired by real operation of the (^{13}C) isotope separation cascade. All simulation tests prove the effectiveness of the control system both for robustness and fault tolerance.

As an example of fault tolerance, the closed loop simulation results, considering a step change in the reference of the first column input, are given in Figure 3. The fault occurs at 500 min in the first column, consisting in an increase of the top pressure due to an inappropriate CO level in the condenser, Figure 3a. The detection unit D1 detects this fault while the reconfiguration unit R1 computes the new set-points, in this case for the first column electrical power in the boiler, Figure 3b, to reduce the bottom pressure in the first column which leads to the decrease of the top pressure, eliminating the negative effect of the fault. The first column waste flow, Figure 3d and feed flow Figure 3e reach their new steady state values. In this case, the overall goal of the system is reached even in the presence of fault.

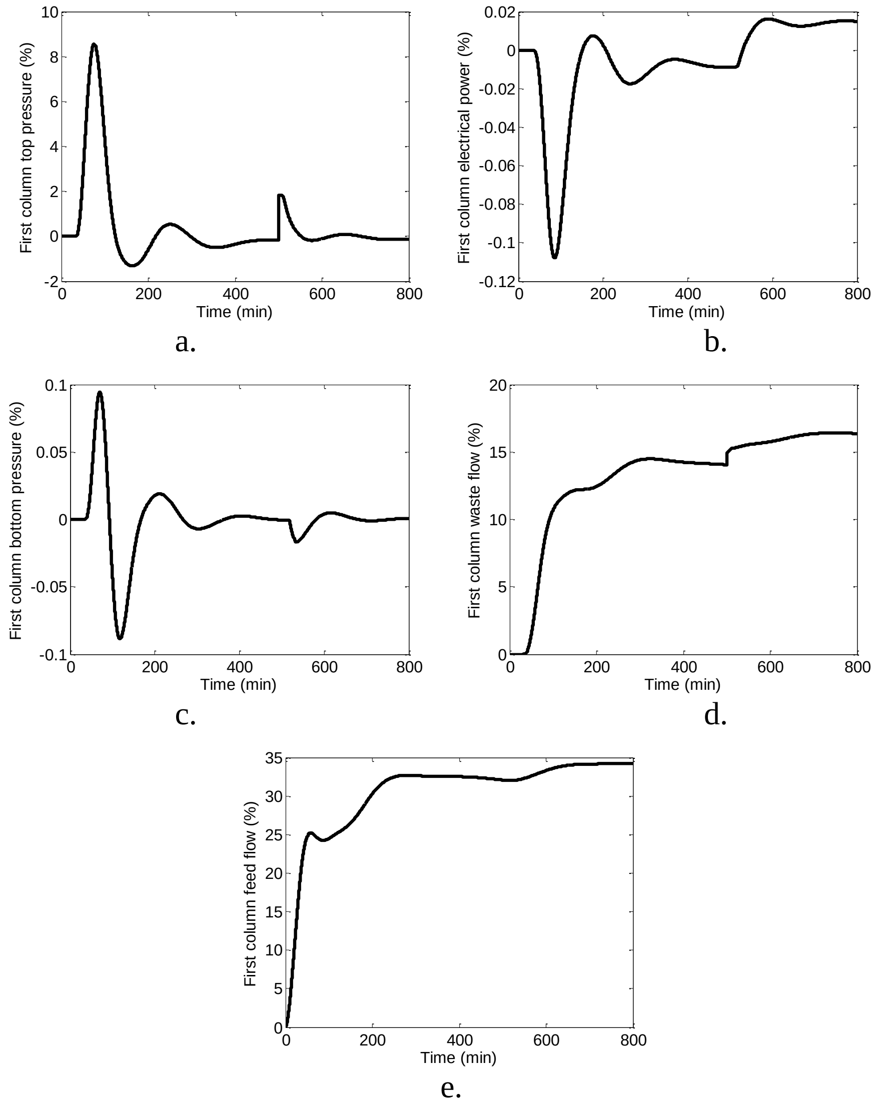


Figure 3. Simulation results for a fault occurring in the first column condenser

A fault in the first column boiler is simulated as another real plant operation scenario. The simulation results are presented in Figure 4. The decrease of the electrical power in the first column boiler at 500 min, Figure 4a, leads to an increase of the bottom pressure in the first column, Figure 4b. The detection unit D1 detects the fault while the reconfiguration unit R1 computes the new setpoints to compensate the fault, resulting an increase of the liquid CO level, Figure 4c, decreasing the first column top pressure, Figure 4d. The effects of the fault to the first column waste flow and feed flow are presented in Figure 4e and Figure 4f.

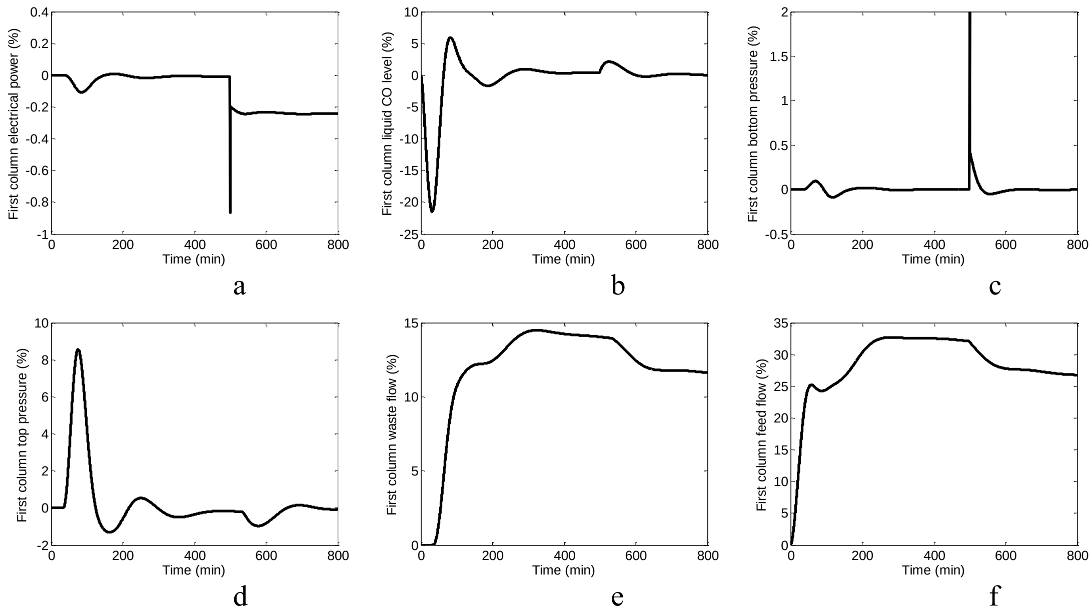
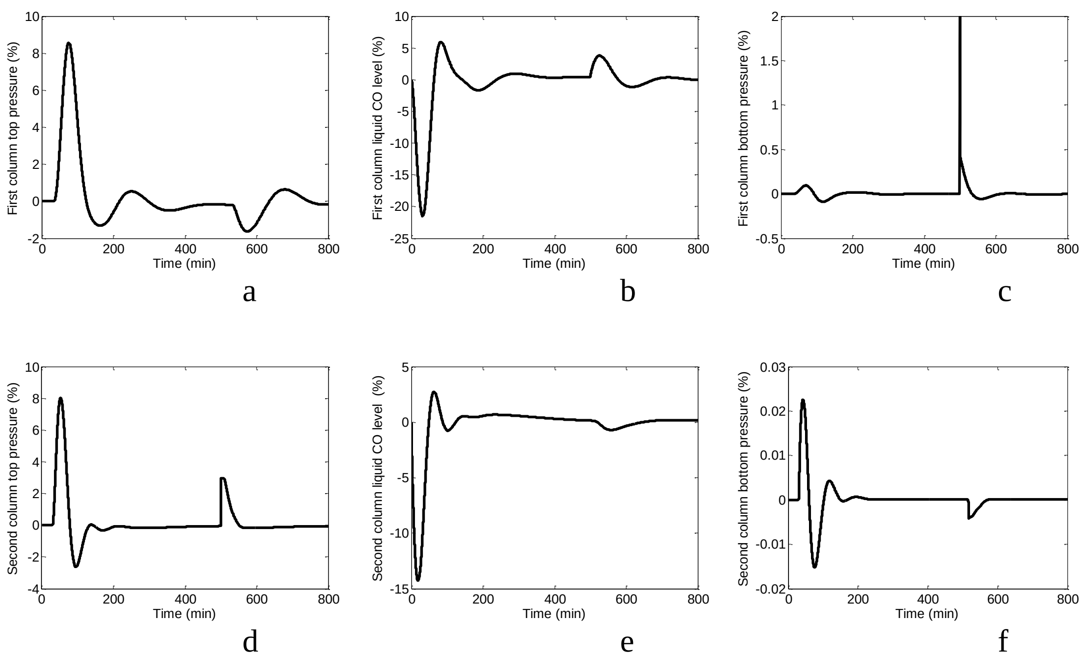


Figure 4. Simulation results for a fault occurring in the first column boiler

In case of fault occurrence in both first and second column, the original productivity can not be achieved any more, but it can be minimized the loss of productivity and can be ensured the safe operation of the process, as it is presented in Figure 5.



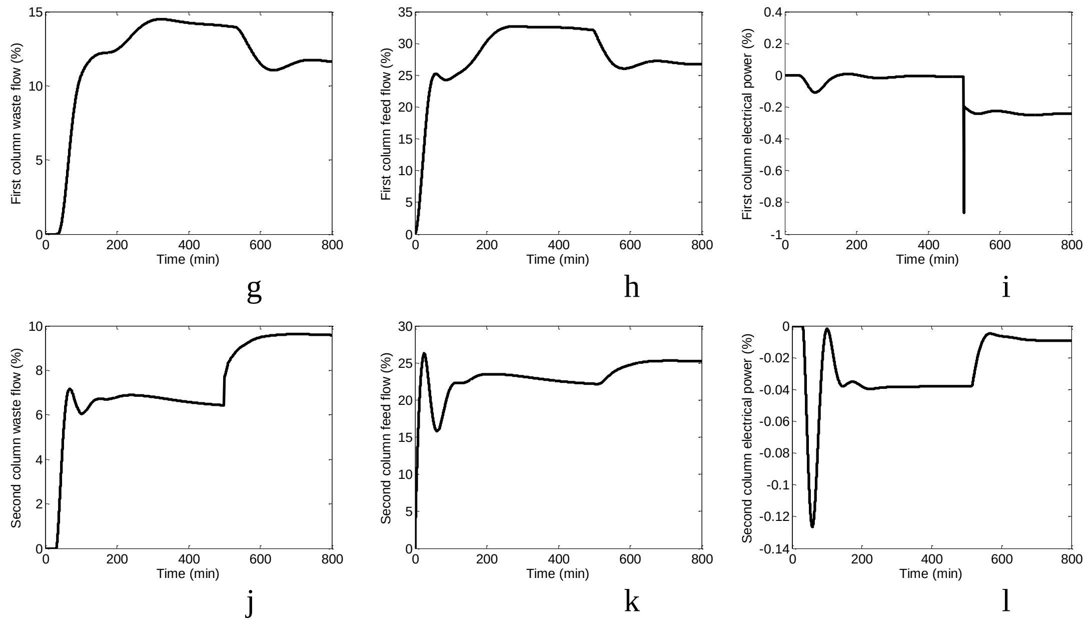


Figure 5. Simulation results for a fault occurring both in the first and second column

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