An optimal control approach for an overall cryogenic plant under pulsed heat loads

Luis Gómez Palacín[1], Benjamin Bradu[1], Enrique Blanco Viñuela[1], Ryuji Maekawa[2], Michel Chalifour[2]

1. CERN, CH-1211 Genève 23, Switzerland
2. ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

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Abstract

This work deals with the optimal management of a cryogenic plant composed by parallel refrigeration plants, which provide supercritical helium to pulsed heat loads. First, a data reconciliation approach is proposed to estimate precisely the refrigerator variables necessary to deduce the efficiency of each refrigerator. Second, taking into account these efficiencies, an optimal operation of the system is proposed and studied. Finally, while minimizing the power consumption of the refrigerators, the control system maintains stable operation of the cryoplant under pulsed heat loads.

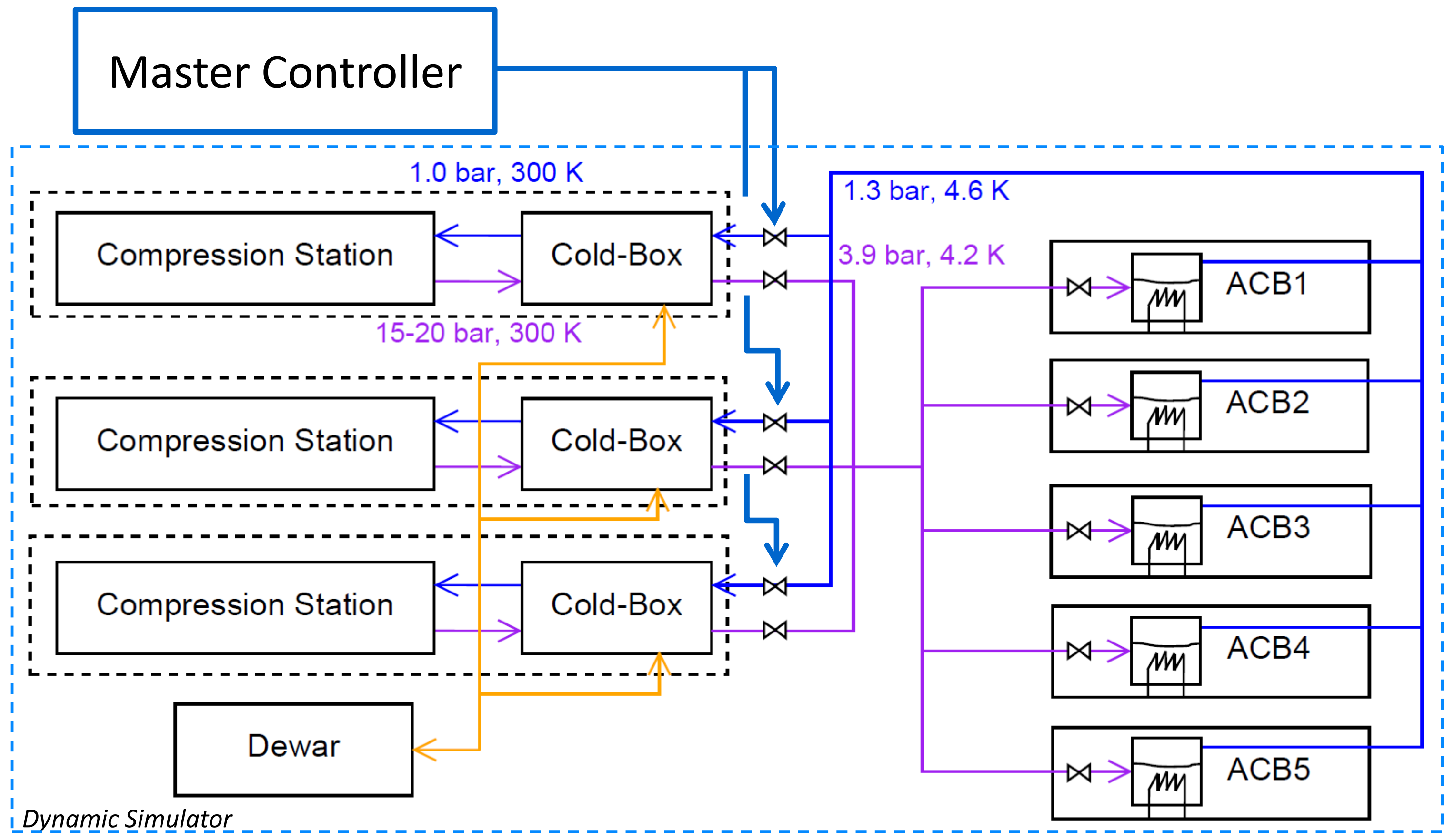
The management of the refrigerators is carried out by an upper control layer, which balances the relative production of cooling power in each refrigerator. In addition, this upper control layer deals with the mitigation of malfunctions and faults in the system. The proposed approach has been validated using a dynamic model of the cryoplant developed with EcosimPro software, based on first principles (mass and energy balances) and thermo-hydraulic equations.

Conclusion

- ❖ This paper describes one possible optimal operation of a cryo-system, consisting of three refrigerators in parallel, which provides supercritical helium to five clients. The total amount of supercritical helium is fixed by the cooling power demand of the clients, however the partial cooling power provided by each refrigerator may vary. A master controller manipulates the production of each refrigerator based on their performance, maximizing the production of the refrigerator with best efficiency and minimizing the production of the worst one.
- ❖ New control schemes have been developed to perform the load balancing between the refrigerators:
    - ❖ Data reconciliation algorithms are executed before each new running campaign.
    - ❖ Optimal balancing between the refrigerators based on the exergy balance is executed at the end of each pulse.
    - ❖ Fault detection system re-equilibrates the load over the refrigerators in real-time.

Methodology

Flow Diagram of the Cryogenic System



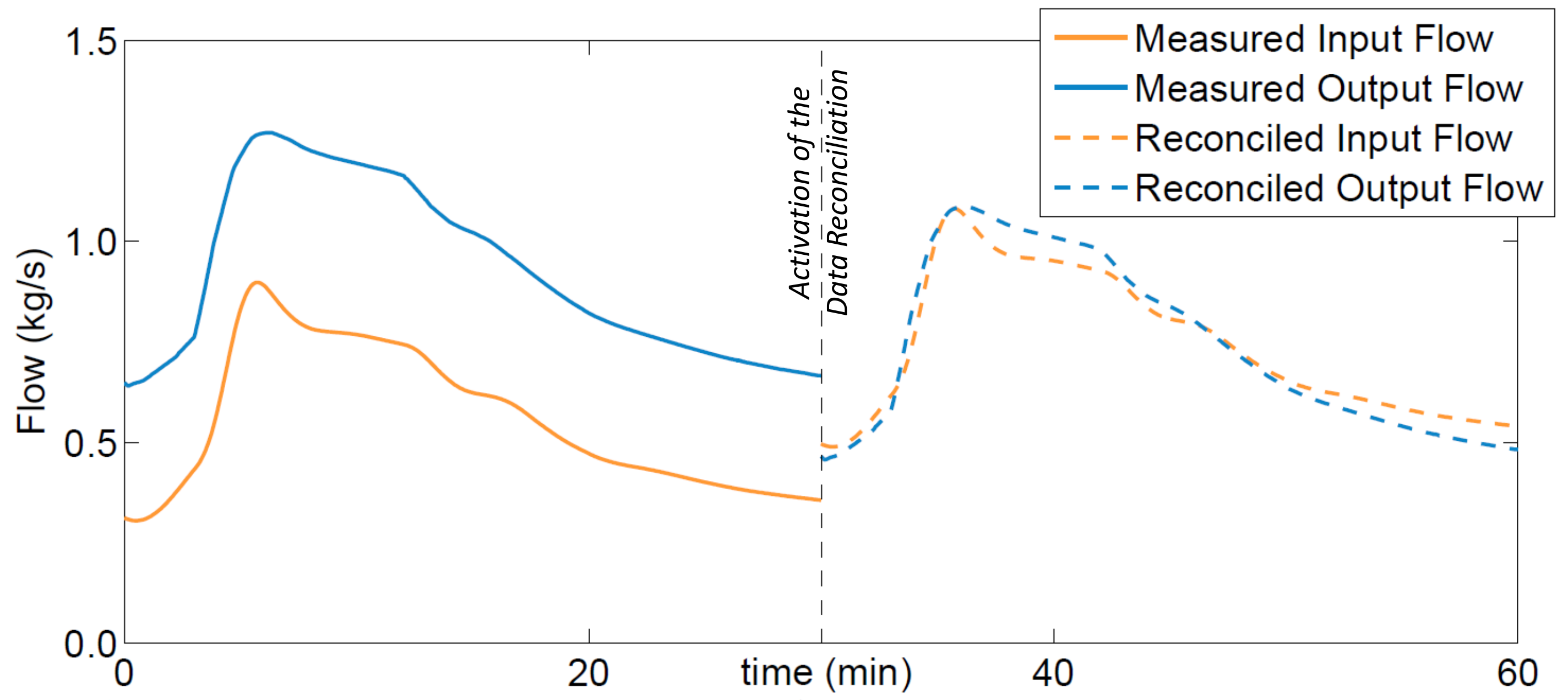
- ❖ A dynamic simulator of the cryoplant, based on first principles, estimates the evolution of the system.
- ❖ A master controller calculates the performance of each refrigerator and manipulates the amount of supercritical helium provided by each one.
- ❖ The efficiency of each refrigerator is inferred from an exergy balance (*B*) of each refrigerator.

$$B_r = \sum_{j=1}^{N} \dot{m} \cdot \left(-T_{ref} \cdot (s_{in} - s_{out}) + (h_{in} - h_{out}) \right)$$

$\dot{m}$ is the mass flow.	T_{ref} is the reference temperature.
s is the specific entropy.	h is the specific enthalpy.
r is the different refrigerators.	j is the different streams.
N is the number of streams.	

Data Reconciliation

Data Reconciliation for ACB Mass Flow



$\dot{m}$ is the estimated mass flow.	$\hat{\dot{m}}$ is the measured mass flow.
L is the estimated level.	$\hat{L}$ is the measured level.
ξ is the range of the sensor.	β is the accuracy of the sensor.
V is the volume of the phase separator.	

- ❖ Data reconciliation is utilized for the estimation of the measurement errors.
- ❖ The data reconciliation solves an optimization problem, which penalizes the errors of the different sensor and satisfies the mass and energy balances.

$$\dot{m}_{in} = a_1 \cdot \hat{\dot{m}}_{in} + b_1 \qquad \dot{m}_{out} = a_2 \cdot \hat{\dot{m}}_{out} + b_2 \qquad L = a_3 \cdot \hat{L} + b_3$$

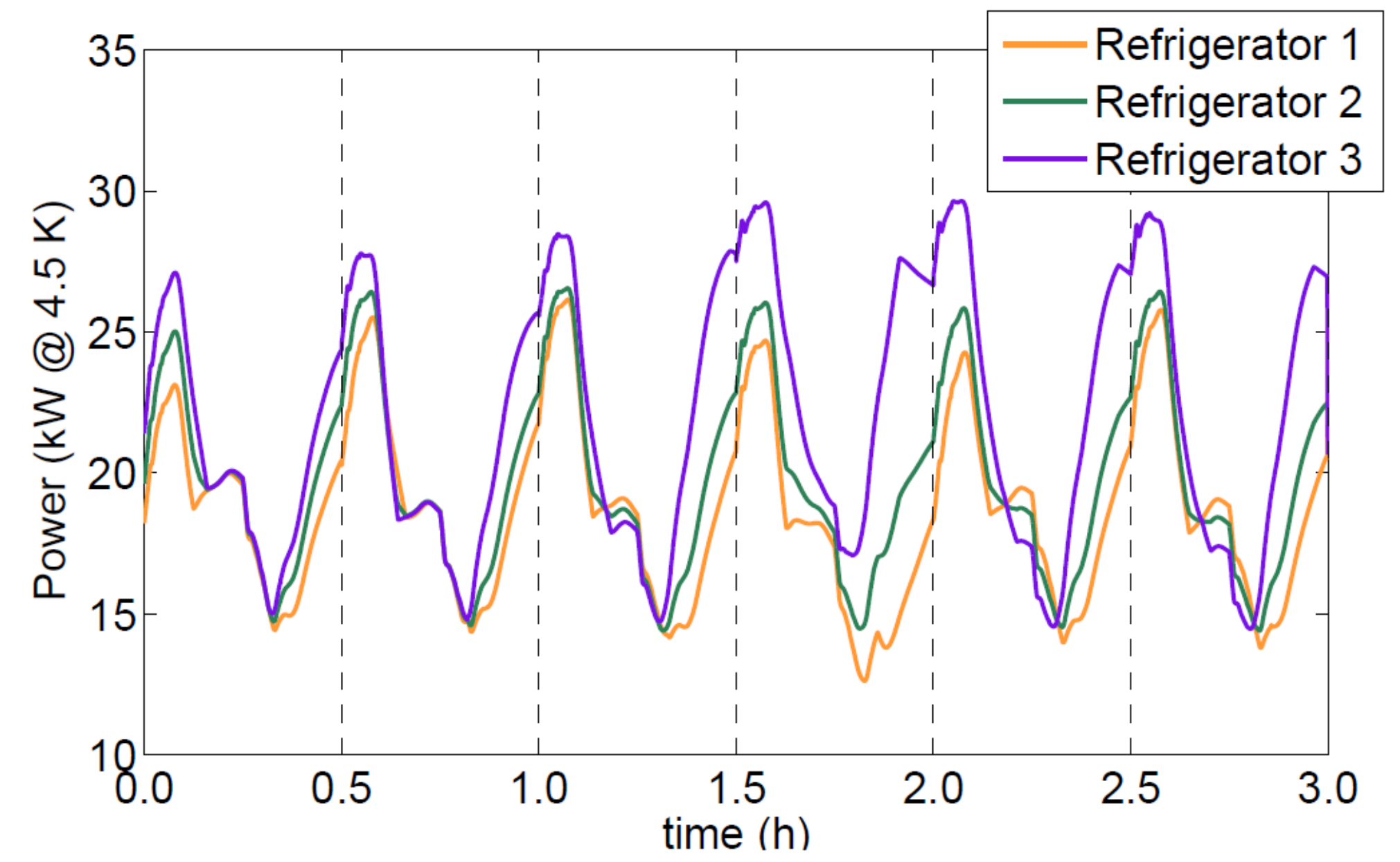
$$\min_{a_i, b_i} \left(\beta_{\dot{m}_{in}} \cdot \frac{(\dot{m}_{in} - \hat{\dot{m}}_{in})^2}{\xi_{\dot{m}_{in}}} + \beta_{\dot{m}_{out}} \cdot \frac{(\dot{m}_{out} - \hat{\dot{m}}_{out})^2}{\xi_{\dot{m}_{out}}} + \beta_L \cdot \frac{(L - \hat{L})^2}{\xi_L} \right)$$

taking into account:

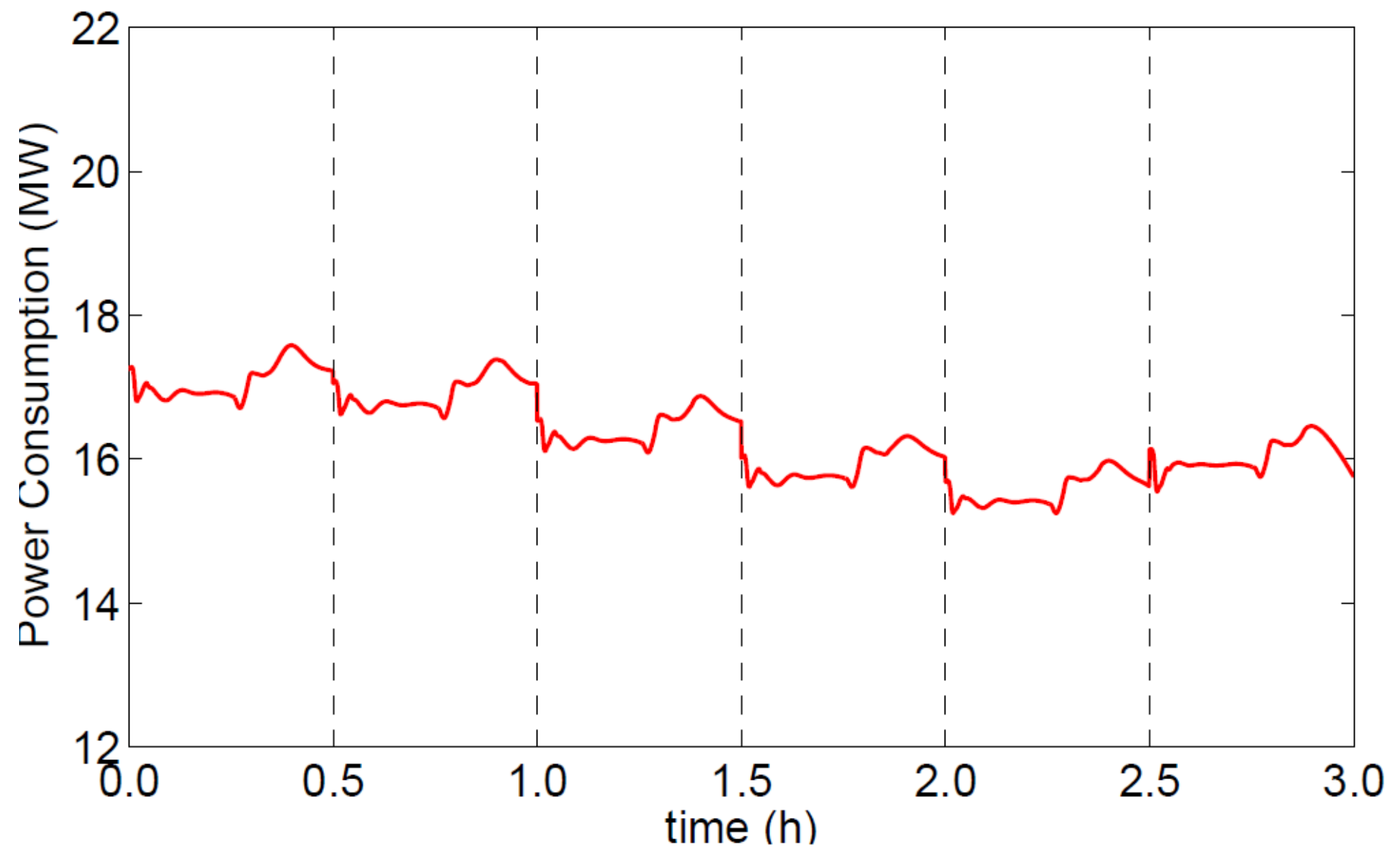
$$\int_{t_1}^{t_2} (\dot{m}_{in} - \dot{m}_{out}) \cdot d\tau = \left(L(t_2) \cdot \rho(t_2) - L(t_1) \cdot \rho(t_1) \right) \cdot 0.01 \cdot V$$

Optimal Operation

Equivalent Power Provided by the three Refrigerators



Power Consumption



- ❖ The actions of the master controller are calculated at the end of each cycle.
- ❖ The manipulated variables (*Δu*) of the master controller are the openings of the valves that connect the refrigerators and the clients.
- ❖ The operating point of each refrigerator is calculated depending on the total equivalent energy (*E*) provided by each refrigerator.

$$\Delta u_r(k+1) = \Delta u_r(k) + K \cdot (E_r(k) - \bar{E}(k))$$

K is a tuning parameter, fixed by the user.

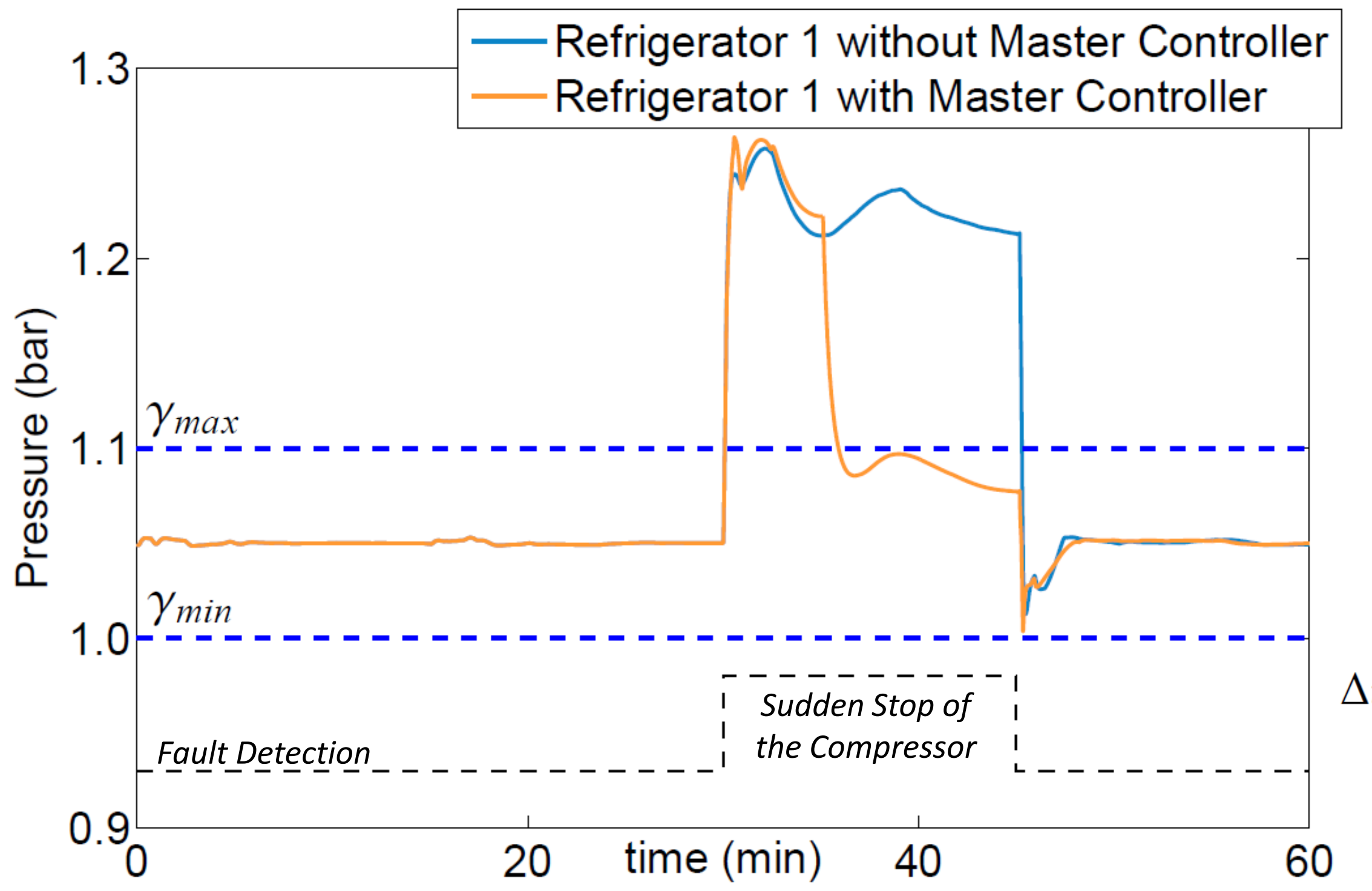
E_r is the energy provided by the refrigerator *r*.

$\bar{E}$ is the average energy of the three refrigerators.

k is the cycle.

Fault Detection

Behavior of the Low Pressure, with Sudden Stop of one Compressor



- ❖ In addition, the master controller deals with the fault tolerance operation of the cryoplant.
- ❖ The actions of the master controller are calculated off-line, by solving an optimization problem, which penalizes the unfulfillment of the constraints.
- ❖ The optimization problem is solved for the different scenarios and possible malfunctions of the system.

$$\min_{\Delta u_r(w)} \sum_{i=1}^{M} \beta_i \cdot \int_{t_1}^{t_2} \left(\max(y_i(\tau) - \gamma_{max\,i}, 0)^2 + \max(\gamma_{min\,i} - y_i(\tau), 0)^2 \right) \cdot d\tau$$

$$y_i \leq \gamma_{max\,i} \qquad y_i \geq \gamma_{min\,i}$$

	γ is the constraints.
$\Delta u_r(w)$ is the manipulated variables.	y_i is the process variables.
w is the changes of the valve position.	i is the controlled variables.
M is the number of controlled variables.	β is the weights.

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