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QUASI-OPTIMAL ALGORITHMS FOR THE CONTROL LOOPS OF THE FERMILAB ENERGY SAVER SATELLITE REFRIGERATOR

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Abstract

The Cryogenic System of the Satellite Refrigerator for the Energy Saver Accelerator Ring comprises 12 interrelated closed loops and several open loops. A quasi-optimal algorithm to control the Cryogenic System, under different modes operation, is described. The constraints imposed to define these algorithms and the process followed to characterize the functional parameters are described. A report on the results obtained with the algorithms in a test facility will be presented.

Introduction

The goal is to obtain an algorithm to control the Refrigerator System that will have the following characteristics:

a. ability to maintain the 12 controlled variables within 1% or better of the set point.

b. minimum complexity and requiring minimum μ-processor time and memory.[1]

c. the same structure for all the different modes of operation of the Refrigerator System.

d. flexible enough to modify its performance, through the change of few parameters as possible, with a predictable behavior.

The development and testing of the algorithms was conducted at the B12 test facility at Fermilab (See Figure 1).

Characterization of the System

The Satellite Refrigerator control is a multivariable control system whose loop behavior can be represented by a vectorial equation of the type

$$C = (\{I\}+\{G\}\{D\})^{-1} \quad (\{G\}\{D\}R+\{N\}P+\{G\}\{D_m\}P_m)$$

with the following definitions (Figure 2).

C - vector representing the controlled variables

R - vector representing the desired values of C

P - vector representing non-measurable perturbations

P_m - vector representing measurable perturbations

{G} - transfer function matrix of the plant

{N} - transfer function matrix for the non-measurable perturbations

{D}, $\{D_m\}$ - matrices representing the controlling algorithms

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Although several methods of attacking the problem of finding suitable {D} and $\{D_m\}$ are presented in the literature[2,3,4] all are cumbersome and result in algorithms of greater complexity than our initial goal will allow.

The classical approach of decoupling the loops by choosing the elements of {D} and $\{D_m\}$ so that

$$\{G\}\{D\} = \{G^*\}$$

where {G*} is a diagonal matrix did not seem to provide enough simplification in the algorithms to warrant its use. Moreover, this approach will not ensure even a suboptimal performance.[2]

Taking this into account, and considering that the Refrigerator System (B12) used as a test bed was in operation for more than one year using independent pneumatic controls, it was decided to approach the problem as if the loops were indeed independent. To achieve success, it was necessary to show that this approach would not introduce unwarranted oscillations.

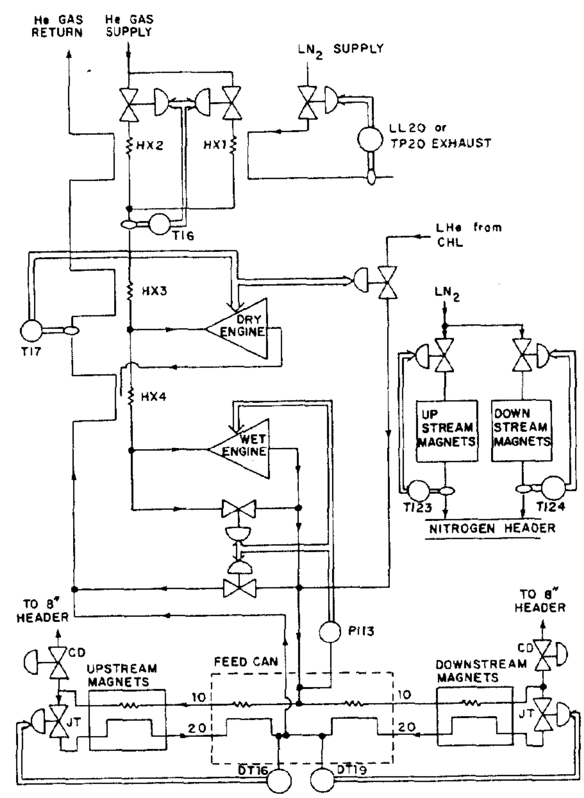

Figure 1. System's Control Loops

Constraints in the Design

To achieve proper control of the Refrigerator System as one unit using independent controlled loops, some constraints in the design of the controlling algorithm were imposed. Such constraints provide for a well be-

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haved system, but allowing for less then optimal response to perturbations.

The constraints imposed are as follows:

1. The closed loop function T(z) must be stable.

2. The loop must reach a quasi-stable status in response to a step function at the input, or to perturbations that can be represented by a step function. This quasi-stable status must be reached in a finite time and this time should be minimized. This constraint can be expressed by:

$$C(nt + kt) = R(nt) + d(nt + kt)$$

$$k \varepsilon I \text{ and } k>0$$

for a change of the type $L\{R(nt)\} = A/s$ and/or $L\{P(nt)\} = A/s$.

3. The corrective algorithm D(z) must be physically realizable.

4. Both the value of the controlling variable M(n) and the correction O(n) = M(n) - M(n-1) must be bounded

$$MINM \leq M(n) \leq MAXM$$

$$MINO \leq O(n) < MAXO$$

5. The sampling interval ST should be smaller than the shortest time constant involved in the loop by at least a factor of 5.

6. The error E(n) = C(n) - R(n), between the controlled variable C(n) and the set point (desired value) R(n), should be less than a predefined value.

Characterization of the Independent Loops

To proceed with the approach outlined above, a series of measurements were taken for each loop to define the transfer functions G(s) of the plant for such loops, as well as an approximation of the response of the plant (for the loop under consideration) to a perturbation generated elsewhere in the Refrigerator System.

This was accomplished by opening the loop at the point where the controlling variable will act (see Figure 2) and introducing a perturbation X(t) of the form $L\{X(t)\} = A/s$. The measured response of the controlled variable was then analyzed in the time domain (the sampling for analysis was chosen to be at least 2 orders of magnitude faster than the expected time response of the plant) and fitted to an expression of the form

$$C(t) = a+bt+g_i\ (1-e^{-t/\alpha_i}) + d\sin(wt)$$

using standard χ^2 fitting techniques. A good fitting was obtained using the simplified expression

$$C(t) = a + g_1(1 - e^{-t/\alpha_1}) + g_2(1 - e^{-t/\alpha_2})$$

with, for all but two cases, $\alpha_1 >> \alpha_2$. Furthermore, maintaining X(t) = A and introducing perturbations in the loop by modifying the dynamics of the overall Refrigerator System, the response was found to be of the form

$$C(t) = \delta(t_0 - t) g(1 - e^{-t/\alpha})$$

with $g << \{g_1, g_2\}$ and $\alpha << \{\alpha_1, \alpha_2\}$, where $\delta(t_0 - t) = 0$ for $t < t_0$, and 1 elsewhere.

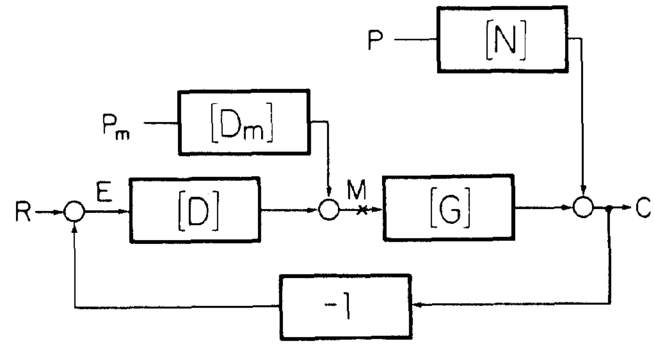

Figure 2. Closed Loop Block Diagram

Control Algorithm

With the data obtained from the tests described above, the approach taken to generate the controlling algorithm follows the classic methods described in the literature[5,6] for minimum settling time. The general expression thus obtained is of the form:

$$O(n) = \sum_{i=1}^{p} A_i M(n - i) + \sum_{j=0}^{q} B_j E(n - j)$$

where O(n) = M(n) - M(n-1) is the corrective action over the controlling variable M(n) to take place at a time t = n*ST with ST being the sampling (correction) interval.

A_i and B_j are, in general, complex functions of the physical characteristics of the system under control, but restricted to the conditions

$$\Sigma A_i = 0$$

$$\Sigma B_j = 1/g;\ g = \text{open loop gain}$$

Expressions for the Parameters

By following the technique explained above of separation of the loops and calculating the open loop gains and time constants (g_i and α_i) the parameters A and B became relatively simple expressions of the open loop parameters.

For a loop with a single time constant, we obtain

$$A = 0$$

$$B_1 = 1/g(1-\gamma)$$

$$B_2 = -\gamma/g(1-\gamma)$$

where $\gamma = \exp\{-ST/\alpha_1\}$.

For a loop with two time constants, the parameters are defined by

$$A_1 = -A_2 = \gamma/(1-\gamma)$$

$$B_1 = 1/g(1-\gamma)$$

$$B_2 = -(\alpha + \beta)/g(1-\gamma)$$

$$B_3 = \alpha\beta/g(1-\gamma)$$

$$B_4 = -\{\gamma - (\alpha + \beta) + \alpha\beta\}/g\ (1-\gamma)$$

where

$$\alpha = \exp\ (-ST/\alpha_1)$$

$$\beta = \exp\ (-ST/\alpha_2)$$

$$g = g_1\ (1-\alpha) + g_2\ (1-\beta)$$

$$\gamma = \{g_1\ (1-\alpha)\ \beta + g_2(1-\beta)\alpha\}/g.$$

Interpretation of the Parameters

By rewriting the general expression for the corrective action in the form

$$O(n) = \sum_{i=1}^{p} A\ M(n-i) + \sum_{j=0}^{q} G_j(\Delta^j E(n))/(ST)^j$$

(where Δ^j denotes the discrete differential of order j respect to t), it is easy to obtain a physical interpretation of the coefficients used in the algorithm. For the simple case of a single time constant, we have:

$$B_1 = G_0 + G_1/ST \qquad B_2 = -G_1/ST$$

and G_0 and G_1 are easily identifiable as the positional and derivative gain, respectively.

Results and Further Developments

Using the algorithms here described, the B12 Refrigerator System, used as test bed, was controlled with excellent results in several modes of operation, including automatic cool-down, ramping of the superconductive magnets with a 4,000A ramp, and automatic recovery from localized quenches. Furthermore, all loops but two (the two corresponding to the JT valves, see Figure 1) were controlled using an approximate response corresponding to a single time constant algorithm. The experimental results seem to validate the constraints imposed and the assumptions made in the characterization of the system. For example, Figure 3 and Figure 4 show the behavior of one loop (dry engine) with pneumatic control, and with microprocessor control using a single time constant algorithm. The improvement obtained is better than one order of magnitude.

The next step will be to implement this type of control in a full system and to define the optimal values of the set points (R(n)) for each loop in each mode of operation of the Refrigerator System.

It is interesting to note that, because the algorithm through the constraints imposed can introduce proper corrections at times other than the normal n*ST time, any unwarranted oscillation introduced in the system is automatically bounded in amplitude.

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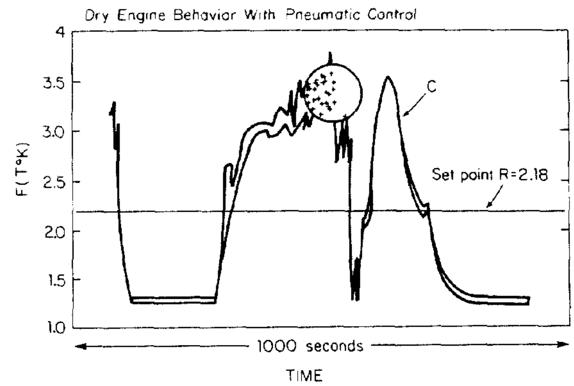

Figure 3

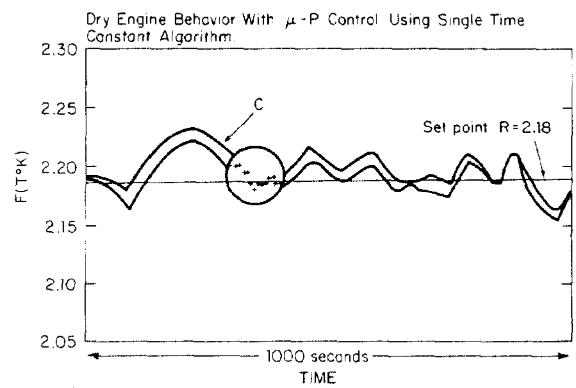

Figure 4

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