CONTROL SYSTEM DESIGN OF THE CERN/CMS TRACKER THERMAL SCREEN

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Abstract

The Tracker is one of the CMS (Compact Muon Solenoid experiment) detectors to be installed at the LHC (Large Hadron Collider) accelerator, scheduled to start data taking in 2007. Since it will be operated at a temperature of -10° C, a thermally insulated environment has to be provided by means of a thermal screen.

The control system design of the thermal screen has been accomplished via a formal description of the process both with a thermodynamic model and the electrical equivalence. A PID (Proportional Integral Derivative) controller has been designed and evaluated using MatLab, along with the finite state machine. The controller has been implemented on a PLC (Programmable Logic Controller).

The results achieved so far prove that this methodology is rigorous, effective and time saving; every step of the procedure is well defined, simplifying the debugging and updating. Besides, the field tests show a good agreement between the model and the real system.

INTRODUCTION

The Tracker extends over a cylindrical region of 2.4 m in diameter and 5.6 m in length. The whole volume will be at -10° C temperature, in order to minimize the radiation damage effects on the silicon detectors [1].

The main task of the thermal screen is to introduce a thermal separation between the Tracker and the neighbouring detection systems (i.e. the Electromagnetic Calorimeter).

Under normal operational conditions, the temperature on the outer skin of the Tracker supporting structure must be that of the average environmental temperature inside the rest of the detector, i.e. 18°C. The temperature uniformity must be less than 2.5°C.

The active thermal screen is made of one heating and one cooling surface separated by a layer of insulating material. The heat flow, naturally due through a surface separating the two volumes at different temperatures, is artificially produced on one side of the screen and removed on the other side [1].

A thermal screen active panel consists of a curved cold plate, a layer of insulating material and a thin heating foil on top. Thirty-two panels, divided in two rows, each one spanning half-length of the Tracker, accomplish the coverage of the detector surface. The control, i.e. the desired profile of the regulated temperature, is produced by heating the foils via a power supply driven by an analog output module of the PLC (Linear Output Control). The quality of the thermal insulation is dependent on the accuracy of the control, whose objective is to guarantee the fastest time response compatible with the system's stability.

The methodology adopted is most general and applicable to a wide variety of process control designs. Moreover, a rigorous documentation is produced, by means of a systems engineering approach (Management Plan, Design Document, Requirements Specifications, Safety Plan, etc). The work has been organized using Project Management techniques (Work Breakdown Structure, Critical Path Method).

In this paper we will deal with three main subjects:

- 1. Modelling the system (designing the electrical equivalent circuit to infer the transfer function in the S-domain).
- 2. Designing the PID controller and investigating stability and performances with the MatLab Control Toolbox.
- 3. Implementing the PID into the PLC, describing the process as a Finite State Machine and running tests.

As for the hardware used, the heating panels are standard Kapton foils with an etched circuit in Inconel, produced in the dimensions 0.45×0.6 m for the specified resistance of 6.1Ω (140 W/m2 @ 48 V); the cold plate is made of two thin aluminium sheets (0.7 mm thick each) joined together in such a way as to produce a spiralling channel (2.5 x 20 mm cross section), through which the cooling liquid flows.

MODELLING

For the control engineering the system can be seen as a process which we must analyse using a dynamical model and finding the mathematical relation that describes the interdependencies between the input and output variables. This can be achieved through a quantitative model obtained via theoretical modelling. The theoretical approach presupposes the knowledge of the physical laws of the process, i.e., a lumped thermodynamic description, as shown in Fig. 1.

The model is built by determining the variables and describing them dynamically through a set of differential equations. Some approximations have naturally to be made, e.g. considering the innermost tracker volume at constant temperature.

The electrical equivalence is shown in Fig. 2; it is derived by substituting the heat source with a current source and the cold plate with a constant voltage generator. The temperature on the outer skin is considered as a variable voltage.

Thermal resistance and capacitance are treated as the analogue electrical quantities.



Figure 1: Thermal Screen thermodynamic model



Figure 2: Electrical equivalency

The circuit can be solved by means of classical network analysis, and the transfer function is defined by the ratio of the voltage on the outer skin and the current input, i.e. the ratio of the temperature outside the tracker and the heat generated (which is the controlled variable). It turns out to be a second order, type zero, over damped system.

$$G(S) = \frac{0.0332}{S^2 + 29.17 \cdot S + 111.9 \cdot S}$$
(1)

DESIGN

The closed loop system can be represented in the block diagram form, as shown in Fig.3, including the PID controller.

The process analysis (both in frequency and time domain) deals with performances and stability. In Fig. 4 we see the Bode diagram along with the step and impulse response: the system shows non-optimal phase and gain margins and low static gain.





In order to achieve stability and satisfy system performances, a PID controller has to be designed. Stability specifications ask for a phase margin greater than 45° and a gain margin better than 20 dB. The general dilemma faced in controller tuning is the compromise between respecting specifications and assuring stability. A PI controller turned out to be a good solution; the tuning has been performed using the Ziegler-Nichols technique. If the controller gain is high, the loop gain will follow, which implies small sensitivity and thus good tracking or good disturbance rejection; hence, a value of KP=16400 has been chosen for the proportional term. The integrator adds a pole in the origin and a zero far from the origin, which results in an integral term Ti=0.02. The controller architecture is parallel, as in the PLC algorithm. The new system behaviour is shown in Fig. 5.



Figure 5: System performances with PI Controller

IMPLEMENTATION

The finite state machine (FSM) representation has been designed using the Stateflow language.

Such a representation is a powerful way for the information exchange between the process engineer and the final users, since it describes the process in a very intuitive fashion.

As shown in Fig.6, the starting point (and default state) is "off". Then, depending on the values of temperature and relative humidity, the system can start heating and regulating. Two alarm classes have been defined: warning (Level 1) and severe alarm (Level 2) which, in turns, can call interlocks either on the Tracker or on the ECAL side or both. The finite state machine is entirely embedded in the PLC software code. The main Stateflow representation is actually made of three more diagrams, each one dealing with separate sub-states which are treated separately: the cooling system and the power supply (along with their own alarm definitions), and the automatic/manual mode selection [3].



Figure 6: Finite state machine

CONCLUSIONS

The methodology hereby introduced has shown to be effective and time saving, thanks to a theoretical (the thermodynamic model) and visual (Finite State Machine, grafcet) description. The rigorous approach in the modelling let the designer cope with every change in the project specification, while the transfer function allows a very fine tuning of the PID. The tests performed with the PLC show a good accordance to the results expected. The documentation produced complies with the systems engineering rules and is an approach extremely useful in every phase of the project, from design to maintenance.

A topic which deserves further investigations is the description of the process as a MIMO (Multiple Input – Multiple Output) system; in fact, the thermal screen modules are prone to show mutual interaction. It means that every input (manipulated) variable affects more than one output (controlled) variable; in that case, a full dynamic matrix control could be envisaged [4].

ACKNOWLEDGEMENTS

The authors would like to thank Guy Baribaud for his lessons on automatic control systems and for the fundamental contributions given during the design stage.

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