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A process and control simulator for large scale cryogenic plants

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ABSTRACT

This paper presents a process and control simulator for industrial helium cryogenic plants controlled by Programmable Logic Controllers (PLC). This simulator can be used for different purposes such as operator training, test of the PLC programs or the optimization of the plant. The different component models used in the simulator are detailed and explained. Various large scale cryogenic plants used for the particle accelerator LHC (Large Hadron Collider) at CERN have been modeled and simulated. The good agreement between the simulation results and the dynamic behavior of real plants is demonstrated with experimental results. Various discussions complete the presentation.

1. Introduction

In 2008, the European Organization for Nuclear Research (CERN) started the most powerful particle accelerator of the world, the Large Hadron Collider (LHC). The LHC accelerates proton beams which are driven by superconducting magnets maintained at 1.9 K over a 27 km ring. To cool-down and maintain superconductivity, large helium refrigeration plants are used, see Lebrun (1999) for more details.

Large scale cryogenic plants are continuous industrial processes, very similar to petroleum (Olsen, Endrestol, & Sira, 1997), chemical (Szafnicki, Narce, & Bourgois, 2004) or sugar industries (Alves, Normey-Rico, Merino, Acebes, & de Prada, 2005). They are composed of the same kind of components (heat exchangers, valves, turbines, compressors, phase separators, etc.) but with additional constraints due to very low temperatures.

Cryogenic plants and their control are highly complex due to the large number of correlated variables on wide operation ranges. Currently, the design and the control of cryogenic systems are based on CERN and suppliers' experience on the process and on appropriate "static" calculations. Due to the complexity of the systems (coupled partial differential equations, propagation and transport phenomena), dynamic simulations represent the only way to provide adequate data during transients.

A new dynamic simulator, PROCOS (PROcess and COntrol Simulator), has been developed to improve knowledge on complex cryogenic systems (Bradu, Niculescu, & Gayet, 2008b). The main objectives of the proposed simulator can be summarized as follows: the operator training, the test of control programs on "virtual" plants before their implementation (virtual commissioning) and the test of new control strategies to optimize the overall behavior of complex systems. This simulator is able to simulate large refrigeration plants using helium and connected to the actual control system of CERN. Furthermore, the existing control policy and supervision systems can be fully reused in simulation. Some advanced control developments as predictive control have already been studied for some LHC cryogenic systems (Blanco, de Prada, Cristea, & Casas, 2009) but it has not been implemented yet and this dynamic simulator can be used to demonstrate efficiency of such controllers.

The superconducting magnets of the LHC were successfully cooled at 1.9 K during 2008. The real operation of the cryogenic plants has started and the use of a dynamic simulator is now the only way to test new control strategies in order to enhance the cryogenic systems without disturbing the LHC operation.

First, various studies devoted to the simulation, analysis and design of cryogenic plants are presented. Next, the simulation approach is outlined in Section 2 and various comparisons with the existent results are proposed. Particular attention has been paid to the simulation architecture and to the explicit modeling approach of the components. Next, simulation results are detailed (CMS cryoplant at 4.5 and 1.8 K unit for the LHC), compared with experimental data and discussed (simulation speed and some comparisons) in Section 4. Some concluding remarks and perspectives end the paper.

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2. Process and control simulation approach

2.1. Existing cryogenic modeling approaches

In various fields of industry, dynamic simulators have been developed to train operators or to design new control techniques, see Alves et al. (2005), Olsen et al. (1997), and Szafnicki et al. (2004). To the best of the authors' knowledge, there exist only a few dynamic simulations devoted to helium cryogenic plants:

- Maekawa, Ooba, Nobutoki, and Mito (2005) have simulated a 10 kW at 4.5 K refrigerator used in a fusion experiment;
- next, Butkevich, Idnic, and Shpakov (2006) developed an educational training tool on a helium liquefier;
- Kutzschbach, Haberstroh, and Quack (2006) have simulated a commercial helium liquefier;
- finally, Deschildre et al. (2008) made simulations on a 800 W at 4.5 K refrigerator.

The proposed simulation approach presents some similarities with the above simulators but it shows also new features and concepts. All simulators perform dynamic simulations by using an object oriented modeling where each cryogenic component is individually modeled by physical differential and algebraic equations (DAEs), excepting the simulator of Butkevich et al. (2006) which is based on mathematical and heuristic modeling.

To model CERN cryogenic systems, a commercial modeling and simulation software was used: EcosimPro© (EA International, 2007). This software was chosen for its flexibility and its ability to export models in C++ classes in order to embed models in larger simulation environments.

All cryoplants that have been modeled are large-scale cryogenic systems. In the adopted object approach, the number of equations is proportional to the number of objects: the complexity of the model is directly linked to the number of the main components, namely the heat exchangers (HXs) and turbines. In terms of numerical computation, large-scale systems can be defined for cryogenic plants containing more than 5 HXs and more than 2 turbines. This configuration generates around 1500 DAEs and it corresponds to a helium refrigerator with a refrigeration power of 400 W at 4.5 K.

All existing simulators have been used only to model helium liquefiers or 4.5 K helium refrigerators. Here, in addition to 4.5 K refrigerators, the modeling was extended to a 1.8 K refrigeration unit using cold-compressors.

Simulations generally include a simplified control in the model. Therefore, most of the existing simulators are not taking into account the real process control and cannot be used as a real-time training simulator, except the simulator of Maekawa et al. (2005). The originality of PROCOS resides in the fact that it is based on the real process control architecture including the supervision system. The process and the control duties are simulated separately and synchronized together. Hence, it allows the simulation of large-scale systems on several computers by decoupling the main parts of a plant.

2.2. Simulation architecture

All CERN cryogenic systems are controlled by industrial programmable logic controllers (PLCs). The control architecture and the control policy are based on an object-oriented hierarchical multilevel and multilayer control framework developed at CERN and called UNICOS. This control framework is based on the IEC 61512 control standard (IEC, 1997); for a complete description of the control system, see Gayet and Barillère (2005).

PROCOS reproduces the UNICOS architecture in simulation even for the three hardware layers as it is shown in Fig. 1. The supervision layer remains the same with operator consoles, PLCs which perform the control are replaced by PLC simulators (softwares) provided by PLC manufacturers and the cryogenic plant is replaced by a cryogenic process simulator integrating *physical equations* of the system.

The same PLC I/O names are used in the process model (inputs are sensors and outputs are actuators). Hence, an OPC server can be configured automatically to establish the link between the PLC and the model. A lot of time can be saved for large applications, see Fig. 2.

The simulation speed is not constant, therefore a synchronization between the PLC and the simulation is necessary: PLC ramps

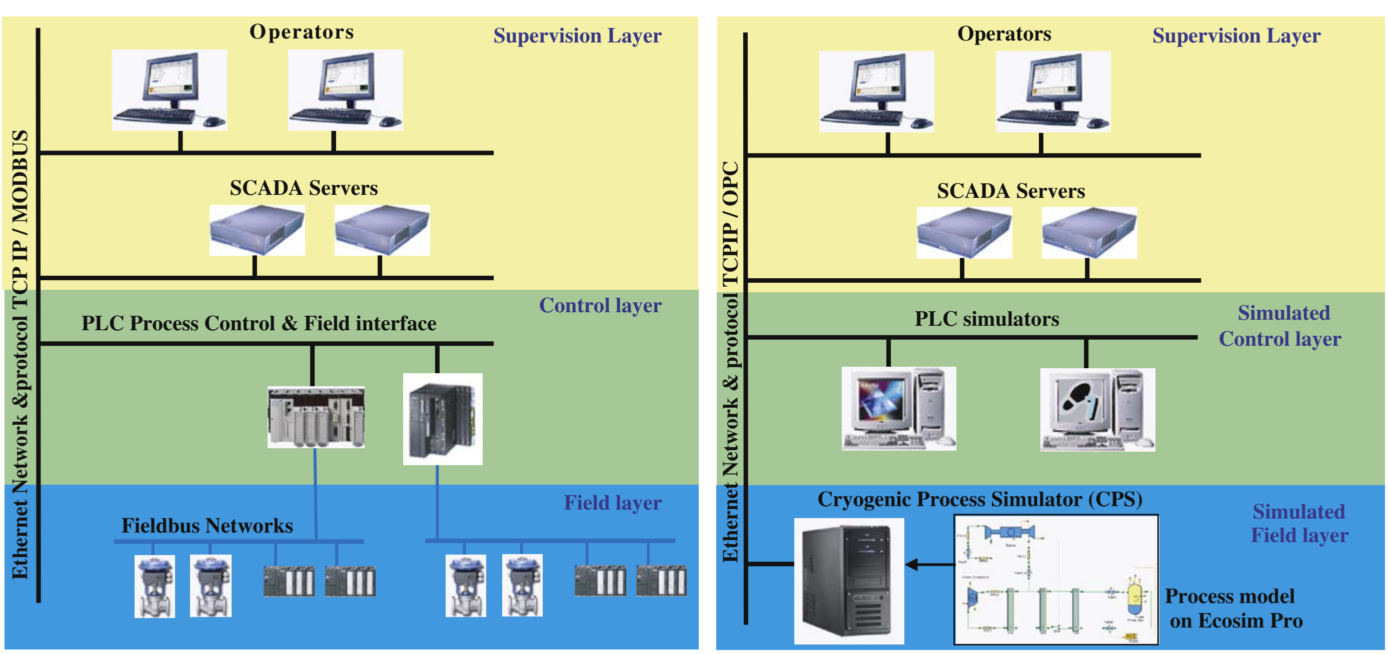

Fig. 1. The real and the simulated control architecture for CERN cryogenic systems.