Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Modeling, Simulation and Control of Large Scale Cryogenic Systems

Benjamin Bradu * **Philippe Gayet** * **Silviu-Iulian Niculescu** **

* *European Organization for Nuclear Research (CERN), CH-1211 Genève 23, Switzerland (e-mail: benjamin.bradu@cern.ch)*
** *Laboratoire des Signaux et Systèmes (L2S, UMR CNRS 8506),CNRS-Supélec, 3 rue Joliot Curie, 91192, Gif-sur-Yvette, France (e-mail: silviu.niculescu@lss.supelec.fr)*

Abstract: This paper presents a dynamic simulator for large scale cryogenic systems using helium refrigerators and controlled by Programmable Logic Controllers (PLC) for the European Organization for Nuclear Research (CERN). The process is modeled by a set of linear differential and algebraic equations and the control policy is based on a hierarchical multilevel and multilayer framework control. First simulation results carried out on the refrigerator used in the Compact Muon Solenoid (CMS) experiment are presented. It is worth to mention that CMS is a particle detector used in the future CERN accelerator (the LHC) where a superconducting magnet of 225 tons, the largest ever built, must be maintained at 4.5K (-268.7^{o}C). The model of this cryogenic plant is composed of 4126 equations whereof 287 differential-algebraic equations. The work objectives of this simulator are threefold: first, to provide a tool to train the operators, second to validate new control strategies before their implementation and, third, to improve our knowledge about large scale complex cryogenic systems. In order to respect the real system architecture, the simulator is composed of different modules sharing data.

Keywords: Complex systems; Time-varying systems; N-dimensional systems; Large scale complex systems; Hierarchical multilevel and multilayer control;

1. INTRODUCTION

The European Organization for Nuclear Research (CERN) is currently achieving the construction in Geneva of the most powerful particle accelerator of the world, the Large Hadron Collider (LHC). Protons will be accelerated in a 27km ring and kept in the right trajectory by superconducting magnets maintained at 1.9K, see Lebrun (1999). The two main particle detectors (CMS and ATLAS) are also using superconducting coils operating at 4.5K. To cooldown and maintain superconductivity in different magnets, large helium refrigeration units are used.

All cryogenic systems are controlled by industrial Programmable Logic Controller (PLC). The control architecture and the control policy are based on a hierarchical multilevel and multilayer control framework developed at CERN.

The cryogenic plants and their control are highly complex due to the large number of correlated variables on wide operation ranges. Currently, the conception, 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 and to validate complete cooldown scenarios.

The CERN control team for cryogenic systems has decided to develop simulation tools to improve the knowledge of these systems and to optimize their management. Within this framework, a dynamic simulator, PROCOS (PROcess and COntrol Simulator) has been developed. It is able to simulate large scale refrigeration plants connected to the actual control architecture. Moreover, the existing control policy and supervision systems can be fully reused in simulation. The main objectives of this work can be summarized as follows: the operator training, the optimization of cryogenic components and the test of new control strategies in order to optimize the overall behavior.

The first simulation test was based on the Compact Muon Solenoid (CMS) refrigerator, cooling the 225 tons cold mass of the superconducting coil down to 4.5K by mean of a thermosiphon cooling circuit, see Perinic et al. (2002).

This approach presents some similarities with other cryogenic simulators developed by other research teams like Kutzschbach et al. (2006); Butkevich et al. (2006); Kundig (2007); Deschildre et al. (2007) in the last years. In particular, the Japanese NFIST research team (National Institute for Fusion Science) which develops the same kind of real-time simulator but with different technologies for a fusion experiment, the LHD (Large Helical Device), where a superconducting coil is cooled by helium, see Maekawa et al. (2005). The originality of our work resides in the fact that PROCOS is based on the *real control architecture*, the *process* and the *control* are *simulated separately*, and allows the simulation of *large-scale systems*.

2. UNICOS, A CONTROL FRAMEWORK

UNICOS (UNified Industrial COntrol System) is a CERN framework developed to produce control applications for three-layer industrial control systems, see Gayet and Barillère (2005). It provides developers with means to perform full control applications and it allows operators to interact with all items of the process from the most simple (*e.g.* I/O channels) to the high level compounded objects (*e.g.* a subpart of the plant). UNICOS proposes also a method to design and develop the control applications. This method is based on the modeling of the process in a hierarchy of objects (I/Os, actual devices and more abstract control objects). These objects are used as a common language by process engineers and programmers to define the functional analysis of the process.

2.1 UNICOS architecture

UNICOS is adapted to industrial control systems, the architecture is built on three layers working at different sampling time (see Fig. 1):

- *The field layer*: it contains the process sensors and actuators connected to the control system.
- *The control layer*: in this layer all the process control tasks are performed by PLC.
- *The supervision layer*: it provides operators with monitoring and command facilities by means of a Supervision Control And Data Acquisition system (SCADA).

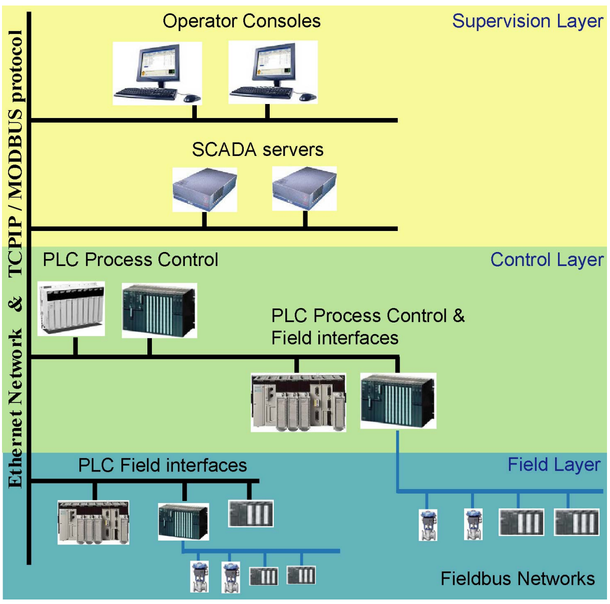

Fig. 1. Industrial three-layer control system

In agreement with the IEC 61512-1 standard (see IEC (1997)), UNICOS proposes to break down the control layer of PLC in a hierarchal organization where each object is controlled by a unique parent in order to constitute a multilevel control. These objects can be sorted in three categories :

- *The Input/Output objects (I/O)* provide the interface to the plant. Here the digitalization process is performed and some basic treatments are carried out.
- *The field objects*, they are the images of the hardware elements such as valves, heaters, motors, and others or they perform control tasks like such as PID loop.
- *The Process Control Objects (PCO)*, responsible for the control of equipment units grouping several field objects and/or other PCOs coping with subparts of the specific equipment.

The I/O and field objects are equivalent to the IEC61512-1 control modules, whereas the PCOs can be considered as IEC61512-1 equipment modules or units according to the level of complexity they handle.

2.2 Generation tools

Tools have been produced to automatically generate PLC objects and their SCADA proxies from a single database, including the communication mapping. The tools also provide means to write application skeletons of PLC codes for different types of PLCs and in case of replication of equipment modules it is possible to use them to generate the complete PLC application.

3. CRYOGENICS MODELING

Cryogenic systems use a limited set of components dimensioned and organized in different ways to reach the requested performances. Previously, in a former study, a theoretical library was developed for the main helium cryogenic components at CERN. This library was created on a standard modeling and simulation commercial software for industrial systems: EcosimPro©. This tool uses differential-algebraic equations with continuous and discrete equations to represent models.

This library has been updated and completed with new components. Models have been modified to cope with data available on real equipments and to improve the "trade-off" between the computational time and the precision. All components were checked individually in simulation and compared with real data to validate such models. A particular attention has been given to component model interconnections in order to obtain robust simulations and to avoid numerical instabilities by taking into account some relevant phenomena and neglecting others, less significant.

3.1 The CMS cryogenic system

The CMS cryogenic system is composed of several units, as follows:

- A *compressor station* located at the surface which compress gaseous helium from 1.03bar to 18bar at 300K.
- A *coldbox* provided by Air-Liquide to cooldown helium from 300K until 4.5K at 1.25 bar. It is located underground in a cavern close to the magnet and it has a cooling capacity of 800W at 4.5K for the magnet, 4.5kW between 60K and 80K for the thermal shield of the screens and 4 g/s liquefaction for the current leads simultaneously. The scheme of the coldbox is shown in Fig. 2.
- An *intermediate cryostat* of 6000l to allow the system an uninterrupted supply of liquid helium in case of failure.

- A *coil cryogenic system* situated above the magnet for the helium supply of the coil. It is composed of a phase separator of 900l connected to cooling sub-circuits via a chimney. The helium flow is driven by a natural thermosyphon principle.

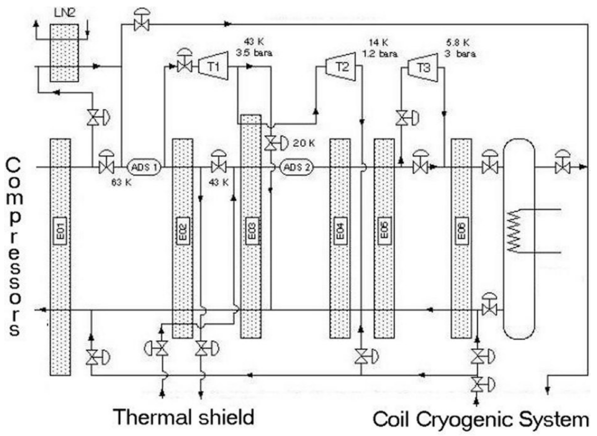

Fig. 2. The CMS coldbox

At the present stage, we have limited the study to the coldbox, the intermediate cryostat and the magnet together. We consider that the compressor station works perfectly under constant boundary conditions.

3.2 Helium properties

All cryogenic components are linked by helium ports (inlets and outlets). A helium port is defined by three state variables which are the massflow and two independent thermodynamic states (*e.g.* pressure and temperature). Helium properties are calculated from this two independent states using the specialized helium library HEPAK©. For large scale systems, linear interpolations are derived from tables obtained by HEPAK rather than using directly the library in order to alleviate calculations. These interpolations allow to save 50% of the calculation time for an acceptable precision.

Some partial derivatives of helium are necessary in component models but such equations are too difficult and too long to solve for these large scale systems. To avoid this problem, we are using the Bridgman's thermodynamic equations which allow to estimate partial derivatives from algebraic equations using a method of generating a large number of thermodynamic identities involving a number of thermodynamic quantities calculated by HEPAK, see Bridgman (1914). Hence, the partial derivatives $\frac{\partial \rho}{\partial h}$ and $\frac{\partial \rho}{\partial P}$ widely used in models, are calculated from (1) and (2) where Cp is the specific heat, v is the specific volume (the inverse of the density: $v = \frac{1}{\rho}$), α is the coefficient of thermal expansion and β is the isothermal compressibility which are given by HEPAK.

$$\left(\frac{\partial \rho}{\partial h}\right)_P = -\frac{\rho^2}{Cp} \cdot \frac{\alpha \cdot v}{T} \tag{1}$$

$$\left(\frac{\partial \rho}{\partial P}\right)_h = -\rho^2 \cdot \left(-\beta v + \frac{T}{Cp} \cdot \left(\frac{\alpha \cdot v}{T}\right)^2 - \frac{v}{Cp} \cdot \frac{\alpha \cdot v}{T}\right) \tag{2}$$

Using these assumptions, all models contains exclusively algebraic equations or linear ordinary-differential equations.

3.3 Component models

All components are defined by a set of differential-algebraic equations (DAEs). First, the total energy E of the fluid in a component is calculated as the product of its mass M and its internal energy u as it is defined in (3). Then, a mass balance and an energy balance are performed by the linear differential equations represented respectively in (4) and (5). $\dot{m}$, h and Q are respectively , the mass flow, the enthalpy and the total heat transfer of the fluid.

$$E = M \cdot u \tag{3}$$

$$\frac{dM}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} \tag{4}$$

$$\frac{dE}{dt} = \sum \dot{m}_{in} \cdot h_{in} - \sum \dot{m}_{out} \cdot h_{out} + \sum Q \tag{5}$$

Finally, according to the component, pressure, mass flow and heat transfers are calculated from others DAEs as follows:

- mass-flows are calculated by valves and turbines according to pressure drops.
- pressures and pressure drops are calculated inside volumes (pipes, phase separators, heat exchangers, magnets) according to inlet and outlet mass flows.
- heat transfers are calculated in each component.

Equation (6) is used to calculate the forced convection heat flux between the working fluid and its enclosure. The global heat transfer coefficient h_c is calculated according to the component. Cp, T and S are respectively the specific heat, the temperature and the surface. The subscript 'W' denotes the enclosure (wall). All properties are estimated at the film temperature $T_f = \frac{T+T_W}{2}$.

Equation (7) is used to calculate the radiant heat exchange between two gray surfaces at temperatures T_1 and T_2, C is constant which is function of the emissivity of the materials, the geometry and the total area.

$$Q_{conv} = M_W \cdot Cp_W \cdot \frac{dT_W}{dt} = h_c \cdot S_W \cdot (T - T_W) \tag{6}$$

$$Q_{rad} = C \cdot (T_2^4 - T_1^4) \tag{7}$$

3.4 Heat exchangers

Different equations are used in the heat exchangers (HX). They are responsible for the main heat transfers in cryogenic systems and they have to be well modeled in order to obtain pertinent results. Heat transfers, mass flows and pressure drops are calculated as functions of design values using a space discretization (each HX stream is divided in N nodes) represented in Fig. 3. A complete HX model is composed of different helium streams exchanging heat across metal walls. State variables for helium in the nodes are the pressure P (assumed constant in all nodes) and the enthalpy h_i in the node i. From this two variables, all other properties can de deduced (temperature, density, *etc.*) using the helium library HEPAK.

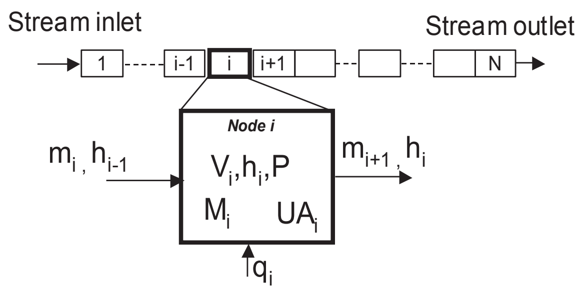

Fig. 3. A heat exchanger stream divided in N nodes

The input massflow of a stream $\dot{m}_1$ is calculated from (8) where nf, ΔP, ρ and μ are respectively the friction factor, the pressure drop, the density and the viscosity. Subscripts 'd' denote the design conditions.

$$\dot{m}_1 = \dot{m}_d \cdot \frac{\sqrt[(nf+2)]{\Delta P}}{\left(\Delta P_d \cdot \sum_{i=1}^{N} \left(\frac{1}{N} \cdot \frac{\rho_d}{\rho_i} \cdot \left(\frac{\mu_d}{\mu_i}\right)^{nf}\right)\right)^{\frac{1}{nf+2}}} \quad (8)$$

The helium enthalpy h_i in each node is calculated by (9) for $i = 1$ to N. Note that the massflow $\dot{m}_{N+1}$ is the outlet massflow which is not calculated by the HX model but by the component to which it is connected and the partial derivatives $\frac{\partial \rho_i}{\partial h}$ and $\frac{\partial \rho_i}{\partial P}$ are calculated as simple algebraic functions as it is mentioned in paragraph 3.2.

$$\left(\frac{\partial \rho_i}{\partial h_i}\right)_P \cdot \frac{dh_i}{dt} = \frac{\dot{m}_i - \dot{m}_{i+1}}{V_i} - \left(\frac{\partial \rho_i}{\partial P}\right)_{h_i} \cdot \frac{dP}{dt} \quad (9)$$

To calculate the pressure P and the massflows $\dot{m}_i$ for $i = 2$ to N, (10) is solved for $i = 1$ to N. Hence, we obtain 10 equations with 10 unknows which are linear in P and $\dot{m}_i$. The term α_i, calculated by (11), is the heat capacity ratio between the wall and the fluid, it allows to take into account the inertia of the heat exchanger. V, M and Cp are respectively the volume, the mass and the specific heat. Subscripts 'W' denote the metal wall of the HX.

$$\frac{dP}{dt} = \frac{\left(\rho_i \cdot (1+\alpha_i) + \left(\frac{\partial \rho_i}{\partial h_i}\right)_P \cdot h_i\right) \cdot (\dot{m}_i - \dot{m}_{i+1}) - Q_i}{V_i \cdot \left(\left(\frac{\partial \rho_i}{\partial h_i}\right)_P + \left(\frac{\partial \rho_i}{\partial P}\right)_{h_i} \cdot \rho_i \cdot (1+\alpha_i)\right)} \quad (10)$$

$$\alpha_i = \frac{M_W \cdot Cp_W}{N \cdot M_i \cdot Cp_i} \quad (11)$$

The term Q_i is calculated using (12) where q_i is the heat transferred from the hot stream to the cold stream using a logarithmic mean temperature difference, see (13), with $\Delta T_i = T_i^{hot} - T_i^{cold}$.

$$Q_i = \left(\frac{\partial \rho_i}{\partial h_i}\right)_P \cdot (\dot{m}_i \cdot h_{i-1} - \dot{m}_{i+1} \cdot h_i - q_i) \quad (12)$$

$$q_i = UA_i \cdot \frac{\Delta T_{i+1} - \Delta T_i}{log\left(\frac{\Delta T_{i+1}}{\Delta T_i}\right)} \quad (13)$$

The global heat transfer coefficient UA_i for the convection between the stream and the wall of each node makes use of the Colburn formulation represented in (14) because the flow is considered turbulent. k is the heat conductivity, μ is the viscosity and Pr is the Prandtl number. Subscripts 'd' denote the design conditions.

$$UA_i = \frac{UA_d}{N} \cdot \frac{k_i}{k_d} \cdot \left(\frac{\dot{m}_i \cdot \mu_d}{\dot{m}_d \cdot \mu_i}\right)^{0.8} \cdot \left(\frac{\mathrm{Pr}_i}{\mathrm{Pr}_d}\right)^{1/3} \quad (14)$$

4. PROCOS

The PROcess and COntrol Simulator (PROCOS) is a set of components interconnected to provide a simulation environment for CERN cryogenic processes. The real process is controlled by a PLC and data are exchanged through generic interfaces as it is showed in Fig. 1.

The simulation environment reuses as much as possible the real control architecture (see Fig. 4). The process is replaced by the Cryogenic Process Simulator (CPS) and PLCs are replaced by PLC simulators provided by PLC manufacturers. The data server and supervision clients remain the sames. All components are communicating on the Ethernet network using an OPC© protocol.

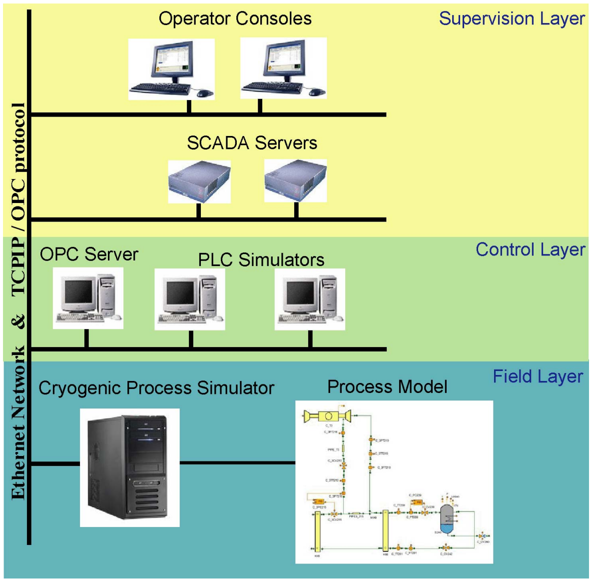

Fig. 4. The PROCOS architecture

The model equations are solved using EcosimPro algorithms. First, symbolic solutions of linear equations for constant coefficients are found. Then, paired algebraic equations are detected to create subsystems. If the subsystem is linear, a linear equations system solver is called to calculate the value of the unknowns. Non-linear algebraic subsystems are solved with a tearing technique which finds a reduced subset of variables (tearing variables) to iterate over them. Then, remaining paired variables can be calculated explicitly as a function of these variables. Iterations are performed until residues between calculated values and expected values are canceled.

Finally, the problem is formulated as a system of differential algebraic equations (DAEs), represented in (15). The solution method is based on replacing the time derivative $\dot{y}(t)$ with an approximation by backward difference as it is shown in (16), see Petzold (1984).

$$F(t, y(t), \dot{y}(t)) = 0 \quad (15)$$

$$\dot{y}(t) = \frac{y_n - y_{n-1}}{t_n - t_{n-1}} \quad (16)$$

Hence, we obtain a non-linear system which can be solved for time t_n using an implicit Newton-Raphson method by iterating. The iteration matrix required by Newton-Raphsons method calculates a Jacobian matrix $\frac{\partial F}{\partial y}$ numerically using finite differences. This implies that discontinuities in models must be explicitly defined in order to perform extra integration steps when discontinuities or discrete events appear to integrate at the right instants and avoid numerical instabilities. A sparse version of DASSL is also used when the sparsity of the final Jacobian matrix is higher than 93%. This method performed a LU decomposition of the Jacobian to alleviate calculations.

5. SIMULATION RESULTS

The CMS experiment and its cryogenic unit are currently in the CMS cavern at 100m underground on the accelerator trajectory since June 2007. Two main simulations have been done :

- A complete cooldown of the cold-box alone in comparison with a cooldown achieved in January 2008.
- A complete cooldown of the cold-box connected to the superconducting magnet and the thermal shield using the intermediate cryostat. This simulation was compared with a cooldown achieved in February 2006 on the surface.

5.1 Process model properties

The complete model of the coldbox connected to the Coil Cryogenic System including the superconducting magnet contains 5874 real variables managed by 4126 equations whereof 287 differential equations. The model takes into account more than 400 parameters to define all components. The Tab. 1 shows the number of UNICOS objects simulated in the model in comparison to the number of objects in the PLC. AI, DI, AO and DO are the Analog/Digital Inputs and the Analog/Digital Outputs. Differences come from useless signals for simulation (*e.g.* hand-valves) or signals which come from non-simulated processes as vacuum systems or power supplies.

Table 1. Number of UNICOS objects

	AI	DI	AO	DO	Field	PID
Real plant	182	326	115	60	156	26
Simulation	138	38	29	15	84	22

5.2 Simulation of the coldbox alone

Simulations have been effectuated with the coldbox alone (without the magnet and its cryogenic circuit). The liquefaction of helium in this operation mode takes 4 hours. We observed the same time in simulation for a computational time of 1 hour and a half. The dynamic behavior simulated agrees to the one observed on the real plant as we can see on the Fig. 5 where the temperature at the beginning and the end of the coldbox is plotted during the cooldown. We can really appreciate the dynamic of the process when the coldbox is cooled alone because when the magnet is connected, 98% of the system inertia come from the magnet. At the end of the cooldown, when the steady-state is reached, a comparison of the temperatures and pressures inside the coldbox was done between the construction specifications and the simulation results. This comparison is as important as dynamic comparisons since it allows to study the equilibrium point of the system with static thermal loads. The maximum relative error observed in simulation is equal to 5% around turbines. This static comparison is satisfactory and shows the accuracy of the model.

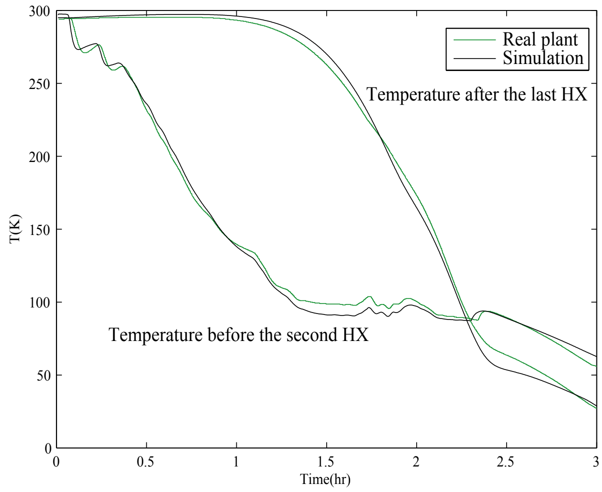

Fig. 5. Coldbox Temperatures

5.3 Simulation of the Coldbox connected to the magnet

The complete cooldown of the magnet takes 23 days. First, the nitrogen precooler allows to cooldown the coldbox until 100K. The two first turbines (T1 and T2) start at 140K and the last turbine (T3) starts at 19K.

The simulation is performed on a Pentium© D 3.4 GHz with 1GB of RAM. In simulation, the complete cooldown of the superconducting magnet from 300K until 4.5K is performed in 4 days of computation time, so the simulator ran 7 times faster than the real process in average. The Fig. 6 presents the simulated magnet temperature compared with real data, the simulated cooldown duration is coherent with the observed one (23 days, 550 hours). The good agreement between the real plant and the simulator shows that the global dynamic of the plant is relatively correct and that the inertia of the system is well modeled, simulation results are realistic. It also means that the different volumes, masses and heat losses of the system are well approximated.

Fig. 7 illustrates the global energy balance of the overall system during the cooldown. The energy balance is calculated as the difference between the input and the output power of the system as it is shown in (17), $\dot{m}$ represents the total mass flow and h is the enthalpy of the gas. Heat is brought to the system by conduction, convection and radiation and heat is extracted by the precooler at the beginning and then by the turbines.

$$\Delta Q = Q_{in} - Q_{out} = \dot{m}_{in} \cdot h_{in} - \dot{m}_{out} \cdot h_{out} \qquad (17)$$

Results obtained in simulation are close to the real ones. Amplitude differences between the real data and the simulation mainly come from the inaccuracy of sensors used on the real plant to calculate this energy balance (an

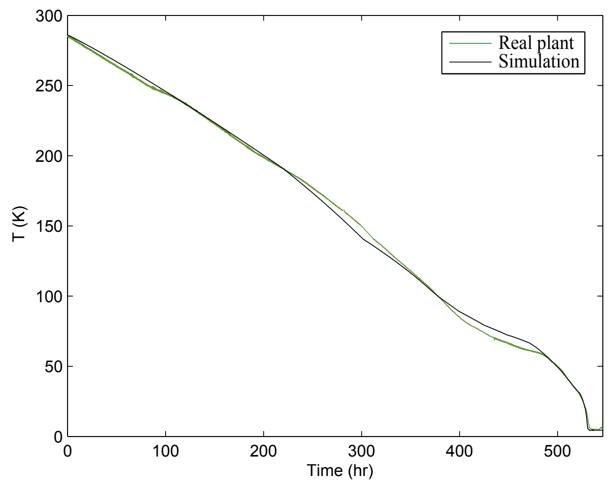

Fig. 6. Magnet temperature

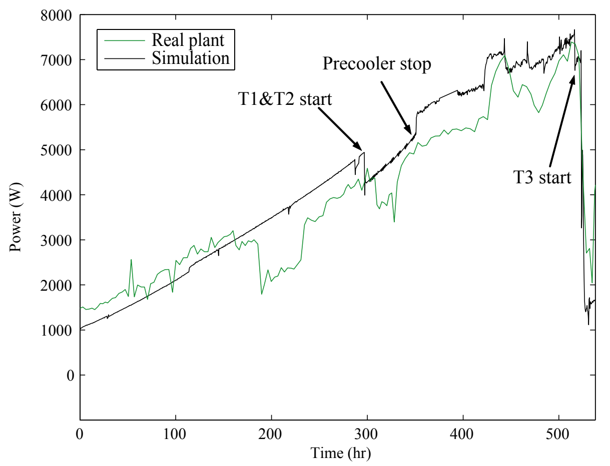

Fig. 7. Energy balance of the overall system

error of 1K on the temperature sensor induces an error of 900 Watt). Moreover, during the real cooldown, operators change manually some regulator set-points (especially on the massflow regulator) or forced manually some valves to optimize the process or to see how the coldbox behaves and it is too difficult to reproduce all of these manual actions.

6. CONCLUSION AND PERSPECTIVES

The basic UNICOS data driven tools alleviate developers from painful and error prone tasks such as object generation in PLC and SCADA and the communication configuration. The advanced model-based production tools are mature and promising.

Concerning the simulations, the evolutions of simulated fluid parameters are coherent to the real ones. PROCOS proved its ability to conduct pertinent dynamic simulations. The simulations of large scale systems are managed by using different simplifications: partial differential equations are replaced by algebraic equations, helium properties are interpolated in tables and a DASSL algorithm is used to solve DAE systems. As the PLC control is reused identically, there is no effort to provide to simulate the control of the plant.

During simulations, several control problems and PLC program errors have been detected. The necessary modifications have been implemented in the real control system to prevent problems for future cooldowns of the installation. In addition, the process engineers of the CMS cryoplant have worked on the simulator and their conclusion is that the simulator behavior is really close to the real plant.

We are now modeling the 2.4kW at 1.8K refrigeration units of the LHC. The goal is to connect this refrigeration unit to a model of the LHC superconducting magnets via the cryogenic distribution line to simulate an entire LHC sector of 3.3 km. This model will allow the study of the control policy improvements by using advanced control techniques in simulation to save energy and to improve the process behavior in case of disturbances.

ACKNOWLEDGEMENTS

Acknowledgments are addressed to Thierry Dupont and Goran Perinic from CERN AT/CRG in Geneva (Switzerland) for their cooperations on the CMS experiment, and also to Hervé Coppier from ESIEE-Amiens (France) for his interest in this project.

REFERENCES

W. Bridgman. A complete collection of thermodynamic formulas. *Physical Review*, 3:273–281, 1914.

I. Butkevich, E. Idnic, and V. Shpakov. Cryogenic helium units simulation model. In *21st International Cryogenic Engineering Conference*, pages 223–226, Prague, Czech Republic, 2006.

C. Deschildre, A. Barraud, P. Bonnay, P. Briend, A. Girard, J.M. Poncet, P. Roussel, and S.E. Sequeira. Dynamic simulation of an helium refrigerator. In *Cryogenic Engineering Conference*, Chattanooga, Tennessee, U.S.A, 2007.

P. Gayet and R. Barillère. UNICOS : a framework to built industry-like control systems, principles and methodology. In *Int. Conf. on Accelerator and Large Expt. Physics Control Systems*, Geneva, Switzerland, 2005.

IEC. Standard IEC 61512-1, Batch control. Part 1: Models and terminology, 1997.

A. Kundig. Recent progress in dynamic process simulations of cryogenic refrigerator. In *Cryogenic Engineering Conference*, Chattanooga, Tennessee, U.S.A, 2007.

A. Kutzschbach, Ch. Haberstroh, and H. Quack. Dynamic simulation of a helium liquefier. In *21st International Cryogenic Engineering Conference*, pages 219–222, Prague, Czech Republic, 2006.

P. Lebrun. Cryogenics for the large hadron collider. *IEEE Transactions on Applied Superconductivity*, 10: 1500–1506, 1999.

R. Maekawa, K. Ooba, M. Nobutoki, and T. Mito. Dynamic simulation of the helium refrigerator/liquefier for LHD. *Elsevier Cryogenics*, 45:199–211, 2005.

G. Perinic, A. Caillaud, F. Dagut, P. Dauguet, and P. Hirel. The helium cryogenic plant for the CMS superconducting magnet. *Advances in Cryogenic Engineering*, 47:232–238, 2002.

L.R. Petzold. *A description of DASSL: a differential-algebraic system solver*. Sandia National Laboratories, 1984.