A DYNAMIC SIMULATOR FOR LARGE SCALE CRYOGENIC SYSTEMS

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Abstract

This paper presents a real-time simulator for large scale cryogenic systems of CERN (European Organization for Nuclear Research) using helium refrigerators controlled by Programmable Logic Controllers (PLC). The results of the first tests carried out on the cold-box used in the CMS (Compact Muon Solenoid) experiment at CERN are also described. It is worth to mention that the CMS experiment is a particle detector used in the future CERN accelerator (the LHC) where a superconducting magnet of 225 tons must be maintained at 4.5K. The work objectives 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 of cryogenic systems. In order to respect the real system architecture, the simulator is composed of different modules sharing data through a standard protocol. The modelling of the process makes use of EcosimPro©, a standard modelling and simulation commercial software for industrial systems. Each cryogenic component is represented by a set of differential and algebraic equations (DAE) and the helium properties are taken from a dedicated helium library. Finally, the control system is simulated with a PLC-simulator provided by the PLC manufacturer. These modules are connected to the real supervision system used to operate the cryogenic plant. Thus, the existing control policy and supervision systems can be fully reused in simulation.

Keywords: Cryogenics, helium, dynamic simulation, EcosimPro, process modelling.

Presenting Author's Biography

Benjamin Bradu. Graduated by the engineering degree of the Graduate School of Electronic and Electrical Engineering of Amiens (ESIEE-Amiens) and by the Master degree of the University of Compiègne (UTC) in 2006, he is specialized in electrical systems and in the control theory. He is currently doing his PhD at the UTC in the CNRS Heudiasyc laboratory working as doctoral student at CERN in Geneva, Switzerland.

1 Introduction

In order to have a better understanding of the matter and its interactions, the CERN (European Organization for Nuclear Research) is currently achieving the construction in Geneva of the most powerful particle accelerator of the world, the LHC (Large Hadron Collider). Protons are accelerated in a 27km ring and kept in the right trajectory by superconducting magnets maintained at 1.9K [1]. 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 PLC (Programmable Logic Controller). The control architecture and the control policy are based on UNICOS (Unified Industrial Control System), a control framework developed at CERN [2].

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 system (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 in such complex interconnected systems.

The CERN control team for cryogenic systems has decided to develop simulation tools to improve knowledge of these systems and to optimize their management. Within this framework, a dynamic simulator, PROCOS (PROcess and COntrol Simulator) is presented. It is able to simulate large scale refrigeration plants connected to the actual control architecture. 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 behaviour.

The first simulation test was based on the CMS (Compact Muon Solenoid) refrigerator, cooling the 225 tons cold mass of the superconducting coil down to 4.5K by mean of a thermosyphon cooling circuit [3].

This study presents some similarities with other cryogenic simulators developed by other research teams [4, 5] in the last years. In particular, the Japanese research team at the NFIST (National Institute for Fusion Science) develops the same kind of real-time simulator but with different technologies for a fusion experiment, that is the LHD (Large Helical Device), where a superconducting coil is cooled by helium [6]. 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 allow the simulation of *large-scale systems*.

2 Cryogenic modelling

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 [7]. This library was created on a standard modelling and simulation commercial software for industrial systems: EcosimPro©. This tool uses algebraic-differential equations with continuous and discrete variables together to obtain hybrid models.

In the present work, 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 avoid numerical instabilities by taking into account some relevant phenomena and neglecting others, less significant.

2.1 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 with two oil-lubricated screw compressors in series providing a mass flow of 207g/s.
- 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 cooling scheme of the refrigerator is based on a Claude cycle, 6 heat-exchangers, 3 expansion-turbines, cryogenic valves and one phase separator are used. A nitrogen precooler can also be used to start the cooldown until 100K. The scheme of the coldbox is shown in Fig.1.
- 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 (see Fig. 2). 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.

2.2 Process simplifications

At the present stage, we have limited the study to the coldbox, the intermediate cryostat and the magnet to-

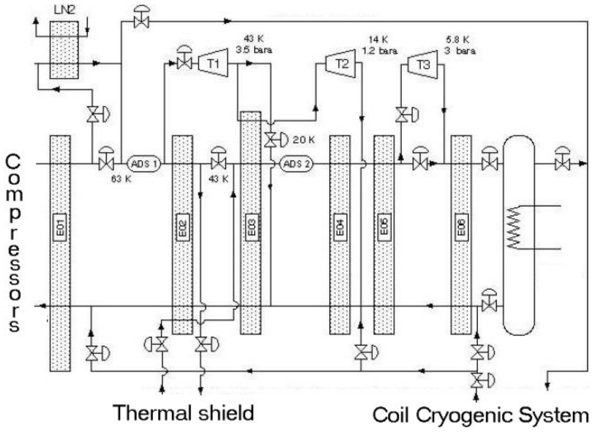

Fig. 1 The CMS coldbox

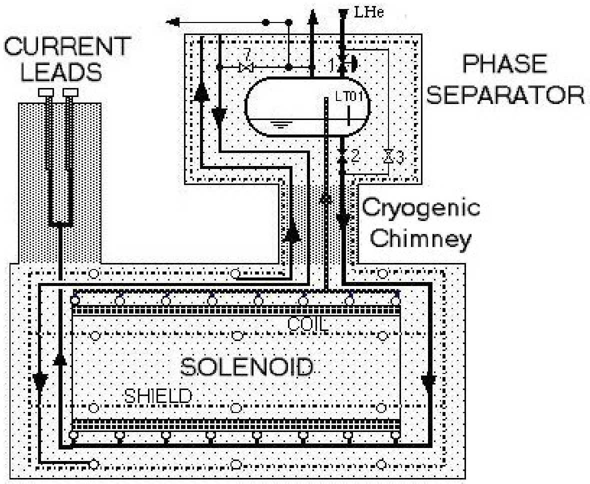

Fig. 2 The Coil Cryogenic System

gether. We consider that the compressor station works perfectly under constant boundary conditions.

2.3 Helium properties

All cryogenic components are linked by helium ports (inlets and outlets). In the model, a helium port is represented by its pressure, mass flow, temperature and enthalpy. Helium properties are characterized by three state variables, therefore, properties have to be calculated from two known states (*e.g.* calculated for a given pressure and temperature). Helium properties are calculated from the specialized library HEPAK© [8]. For gaseous helium with a temperature above 5K, linear interpolations are developed from tables, otherwise the HEPAK library is directly used online. Interpolations with small intervals allow a faster calculation of helium properties with a sufficient accuracy, whereas for temperatures below 5K or when helium becomes liquid, interpolations are inaccurate due to the high nonlinearities of helium properties (like specific heat and density). Partial derivatives are calculated from the Bridgman's thermodynamic equations [9].

2.4 Heat exchangers

The coldbox contains 6 plate-fin counter-current heat-exchangers in brazed aluminum grouped in three blocks. Each heat-exchanger is defined by a set of parameters at designed condition: global heat transfer coefficient, pressure loss, temperature, pressure, mass flow, mass, volume and aluminum heat capacity of each stream. Heat transfer and mass flow are calculated as functions of design values using a space discretization (each HX is divided in several nodes). For multi-stream heat-exchangers, we consider only the heat transfer between hot flows and cold flows. The temperatures of the metal wall and of the fluid are considered equal.

2.5 Turbines

Turbines are used to cooldown helium by expansion. The model uses the following design parameters: inlet and outlet pressure, inlet temperature, shaft speed, mass flow, adiabatic efficiency, rotor blade diameter and inertia moment of the rotor. The mass flow rate and the outlet temperature are functions of the pressure drop and of the inlet temperature. There is no mass accumulation inside turbines and forward flows only are considered. A hybrid model is used to cope with the different behaviours of the flow inside the turbine as the mass flow can be subsonic or sonic.

2.6 Cryogenic valves

For cryogenic valves, the Cv formulation (valve coefficient) is used and the transformation is considered adiabatic without any mass accumulation. Valves can be either on-off or with a variable opening (equal percentage or linear). A pressure drop ratio factor is included in the equations according to the type of valve (butterfly, ball, angle...) and an hybrid model is used to take into account sonic and subsonic flows.

2.7 Phase separator

The system includes three phase separators (one in the coldbox, the intermediate cryostat and one before the magnet for the thermosyphon circuit). The mixture liquid-gas is considered as well mixed (temperature is uniform) and radiative losses are taken into account.

2.8 Pipes

Volumes and masses are not considered in component models except for the heat exchangers and phase separators. If two components are connected together without considering volumes or masses (*e.g.* two valves in series), numerical singularities or non-linear algebraic loops may appear due to this direct link. The solution consists in introducing helium pipes between components. These pipe components allow the model to represent buffer and delay effects which occur in the real plant, thus the model becomes more robust, including some of the environment constraints.

Equations to represent pipes are mass and energy balances calculating the derivatives of helium mass and helium internal energy inside volumes. The global heat transfer coefficient is considered constant and the pressure drop can be taken into account for long pipes.

2.9 Superconducting magnet

The superconducting magnet model includes the magnet embedded in a thermal shield (thermal screen). The magnet and the thermal shield are considered as aluminum masses containing an helium volume with a pressure drop. The magnet exchanges heat with the helium flow by convection and with the thermal shield by radiation. The thermal shield exchanges heat with the ambient air by radiation. This thermal shield allows the magnet to minimize heat losses by radiation which is the dominant mode of heat losses at low temperatures.

3 Description of 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.3). Then, all necessary process information contained in the PLC are stored in a data server via the ethernet network using a MODBUS© protocol. Supervision clients using the software PVSS (the Operating Work Stations, OWS) can be connected to the data server to read process information but also to send order to the PLC for manual operations.

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

All data are exchanged through OFS (OPC Factory Server), an OPC Server provided by the PLC manufacturer where all PLC data can be read and written by OPC clients (CPS and the data server).

3.1 The Cryogenic Process Simulator

EcosimPro© allows the exportation of the model designed in a C++ class which is integrated in the Cryogenic Process Simulator (CPS). CPS is an application written in C++ to link the process model and the PLC.

The PLC gives orders to CPS, then EcosimPro algorithm finds the solution of the model at the next sampling time and, finally, new values of the process sensors are sent to the PLC.

To minimize the computational time and the data exchanges, all communications are asynchronous between CPS and the PLC.

Some options are available for simulations like saving and restoring a precise state of the process. It's also possible to run the simulator as fast as possible or in real-time.

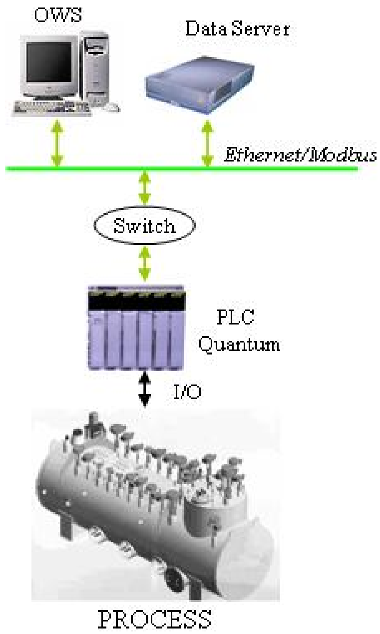

Fig. 3 The real process architecture

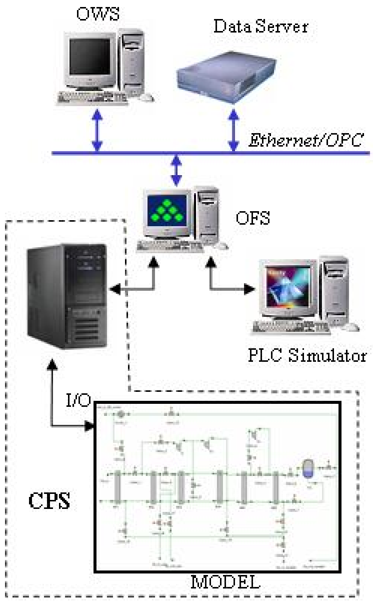

Fig. 4 The PROCOS architecture

3.2 Synchronization

The PLC program is executed in real-time whereas the process simulation can be faster or slower. This phenomenon induces problems for ramp generators and PID control as these two algorithms take internal time of PLC as reference. To avoid this problem, the PLC program has been modified accordingly: PID outputs and ramp generator outputs are not calculated inside the PLC anymore but directly in the simulator and these phenomena become transparent.

3.3 Numerical algorithms

The model is solved at each sampling time by CPS using EcosimPro algorithms [10]. First, symbolic solutions of linear equations for constant coefficients are found. The linear algebraic subsystems are solved by a linear equation solver and 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 finding. Iterations are performed until residues between calculated values and expected values are canceled. In the coldbox model, the subset of tearing variables are pressure drop ratios of valves. Finally, EcosimPro uses a DASSL algorithm (Differential-Algebraic System Solver) to solve numerically differential and algebraic equations. The solution method is based on replacing the time derivative $\dot{y}(t)$ with an approximation by differences and then solving the resulting equations for time t_n using an implicit Newton-Raphson method by iterating.

4 Simulation results

The CMS experiment and its cryogenic unit are currently in construction in the CMS cavern at 100m underground on the accelerator trajectory. The first real data in situ should be available around November 2007. Nevertheless, we have validated our simulation results with a test carried out in February 2006 at the surface with the coldbox connected to the superconducting magnet.

During this test, some valves have been forced and some set-points were changed by operators to optimize the cooldown or to see how the coldbox behaves. Most of these manual actions were not taken into account in the simulations where the control is automatically done by the PLC program.

The simulation has been made with the same configuration than the real test with the coldbox connected to the Intermediate cryostat and to the Coil Cryogenic System including the superconducting magnet of 225t with the thermal shield. The simulation covers the cooldown from 300K until 5K just before the liquefaction of helium.

4.1 Process model properties

The complete model of the coldbox connected to the Coil Cryogenic System including the superconducting magnet is composed of 3943 algebraic-differential equations, the Tab. 1 summarizes the different model informations and the Tab. 2 shows the number of electrical I/O simulated in the model and the number of exchanged signals between the PLC and the process simulator.

4.2 Cooldown sequence

After the connection of the coldbox to the compression station and to the magnet, the cooldown sequence is divided in 4 main steps described in the Tab. 3. First, a nitrogen precooler is used alone until 140K, then the two fist turbines start (T1 and T2) and the precooler is stopped at 85K. The final part of cooling is done with the last turbine (T3) from 20K until the liquefaction at 4.5K. The complete cooldown of the 225t of the magnet is achieved in about 23 days as it is extremely important to not exceed a temperature difference of 40K on the coil to avoid destructive mechanical stresses.

Tab. 1 Model informations

info	**Number**
Equations	3943
Coupled subsystems of equations	15
Linear subsystems:	14
Nonlinear subsystems:	1
Explicit variables:	3713
Derivative variables:	228
Algebraic variables:	2
Boundary variables:	323
Size of Jacobian matrix:	230
Sparsity factor in Jacobian matrix :	86%

Tab. 2 Number of electrical I/O

	AI	DI	AO	DO	PID
I/O Simulated	138	38	29	15	18
Exchanged signals	301	38	77	53	x

Tab. 3 Cooldown sequence

step	T_{mag}(K)	time(day)	Preco	T1+T2	T3
1	300-140	14	x		
2	140-85	3.6	x	x	
3	85-20	5.4		x	
4	20-4.5	0.25		x	x

4.3 Cooldown simulation

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 5K is performed in 3 days of computation time, hence the simulator ran 7.5 times faster than the real process in average. The simulated cooldown duration is coherent with the observed one (23 days). The Fig. 5 presents the simulated magnet temperature compared with real data, we can note that the simulated cooldown is a little bit faster for the most part of time except after the precooler stop. These differences come from manual operations that have been done on the real process. For example, the setpoint of the mass flow was changed several times on the real plant but not in simulation (see Fig. 6).

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 modelled. It also means that the different volumes, masses and heat losses of the system are well approximated.

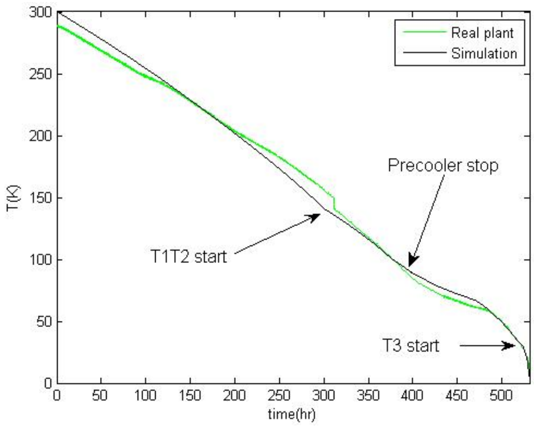

Fig. 5 Magnet temperature

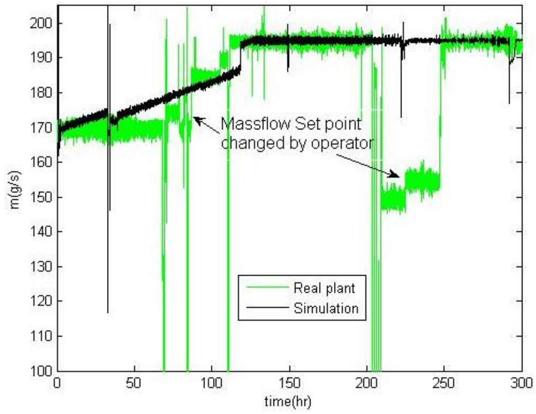

Fig. 6 Total mass flow (during step 1)

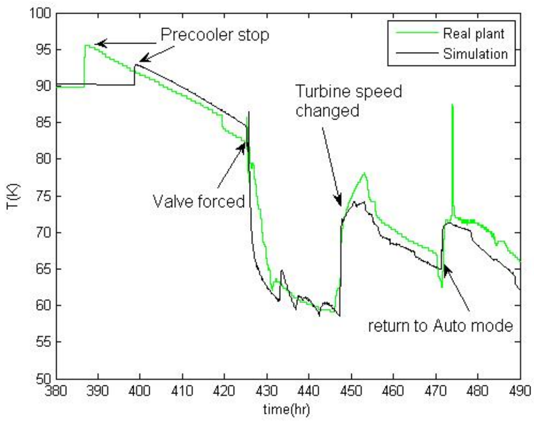

Fig. 7 Temperature after the first heat exchanger during unusual operation

During the test on the real plant, process engineers forced some important valves and changed set-points on the turbine speeds when the magnet was around 75K to see how the coldbox behaves. These manual actions disequilibrated temperatures and pressures in the coldbox and they returned to the normal operations after 60 hours. We tried as well as possible to reconstitute these manual actions in simulation to allow dynamical com-

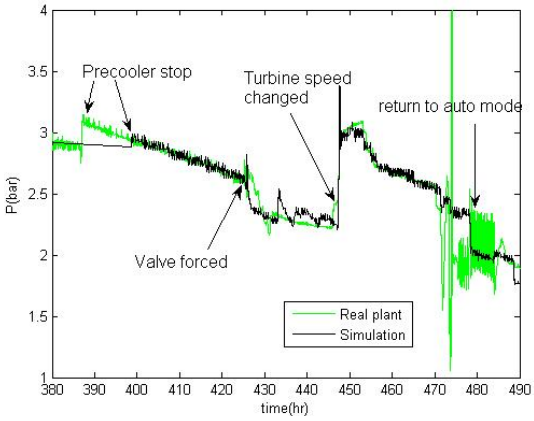

Fig. 8 Pressure in the coldbox phase separator during unusual operation

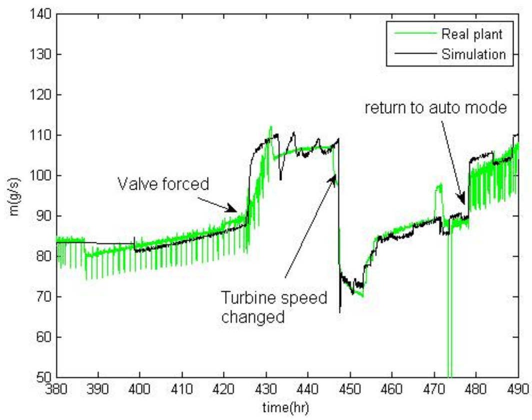

Fig. 9 mass flow of turbine 1 during unusual operation

parisons of the transient for an unusual operation of the coldbox. Figs. 7, 8 and 9 represent the temperatures after the first heat exchanger, the pressure in the coldbox phase separator and the turbine mass flow during these manual operations. The behaviour simulated is coherent with the one observed on the real plant and simulation results are realistic.

Figs. 10 and 11 illustrate the global energy balance of the overall system and the energy balance of the Coil Cryogenic System alone during the cooldown. Results obtained in simulation are close to the real ones, hence the energy behaviour of the system is validated. The energy balance is calculated as the difference between the input and output power of the system: $\Delta Q = Q_{out} - Q_{in} = \dot{m}_{out} \cdot h_{out} - \dot{m}_{in} \cdot h_{in}$ where $\dot{m}$ represent the total mass flow and h the enthalpy of the gas. Heat is brought to the system by conduction, convection and radiation (positive power) and heat is extracted by the precooler at the beginning and then by the turbines (negative power). In simulation, heat losses by conduction are neglected because of their low values in comparison with the heat losses by convection and radiation at cryogenic temperatures. Main heat losses are located in the Coil Cryogenic System (the magnet with the thermal shield) but also in phase separators (radiation) and in pipes (convection).

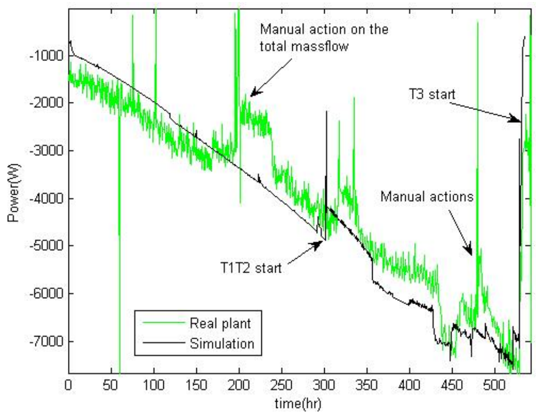

Fig. 10 Energy balance of the overall system

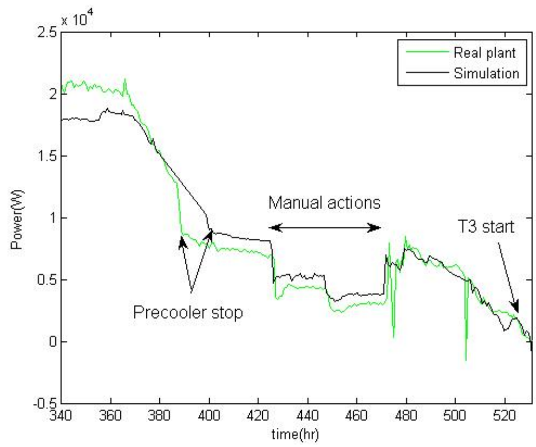

Fig. 11 Energy balance of the Coil Cryogenic System

4.4 Coldbox alone

Simulations have also been effectuated with the cold-box alone (without the Coil Cryogenic System) but the absence of real data does not allow dynamical comparisons. Nevertheless it is possible to compare the steady-state reached at the end of the helium liquefaction with the design parameters of the cold box.

The design conditions are reached in simulation after 6 hours (4g/s of liquefaction, a 4.5kW available between 60K and 80K and a 800W available at 4.5K). For this static situation, the computed T-S diagram (the temperature plotted in function of the entropy) is represented in Fig. 13 together with the theoretical T-S diagram supplied by Air-Liquide for design conditions. All points of the thermodynamical cycle are closed to the specifications with a maximal relative error of 4%. This static comparison is as important as dynamic comparisons since the exactitude of the T-S diagram confirms that the temperature and pressure repartition inside the cold-box is correct and that the different heat transfers are well modelled. Note that the cold box alone will be tested in October 2007 before a connection with the magnet and so, dynamical comparisons will be possible soon.

4.5 Simulator speed

Fig. 12 represents the ratio between the real process time and the computational time of simulation. An average of the speed is calculated at regular intervals. According to the operating point, simulation speed changes due to the different process operations. For example, when turbines start all actuators are moving and the simulator needs more calculation time to find convergent solutions. The speed can be increased maximizing the integration step size of the simulation solver but it is important to conserve an integration step inferior to the fastest dynamic of the process. Typically when regulating valves move a lot, it is necessary to have an integration step around 2 seconds whereas when valves remain relatively constant, the integration step can be increased up to 20 seconds. During a normal operation, the simulator can be 25 times faster than the real process with an integration step of 20 seconds and 5 times faster with an integration step of 2 seconds. This step can be changed on-line during simulation to maximize the speed. Note that for operator training, it is possible to active a real-time option in the simulator.

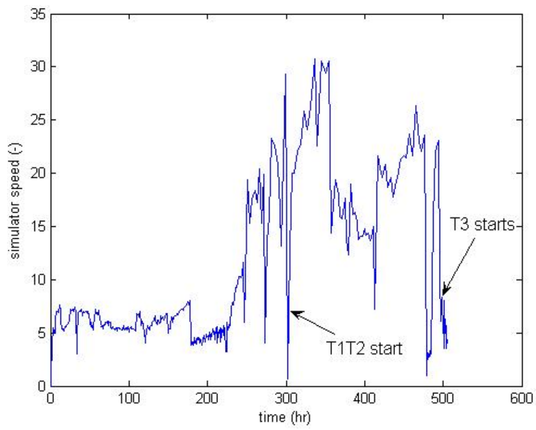

Fig. 12 Simulator speed

5 Conclusion and Perspectives

The evolutions of simulated fluid parameters are coherent to the real ones and the different static states are very close to the construction specifications.

The simulation of the liquid helium for the coldbox alone works perfectly but there are still some problems in the Coil Cryogenic System when helium becomes fluid due to the complexity of the model for the thermosyphon circuit. This part of the model have to be improved before going ahead in simulations with liquid helium inside the magnet.

PROCOS proved its ability to conduct pertinent dynamic simulations for large scale cryogenic systems during a complete cooldown. These first simulations allowed the validation of the component models and the simulation environment. Simulation speed is always faster than the real-time except during some short

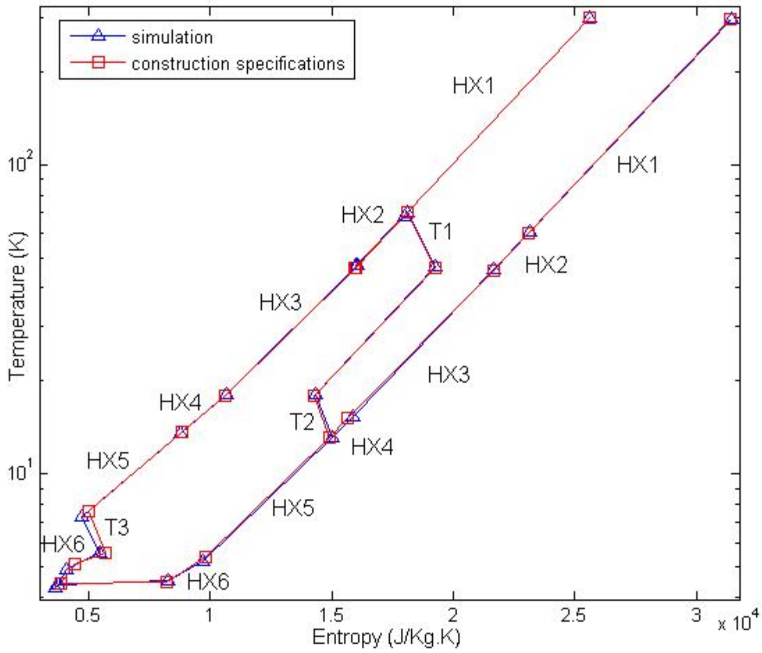

Fig. 13 T-S diagram of the coldbox at 4.5K

transients like the turbine start. Hence, the "trade-off" between the computational time and the precision is in agreement with the requirements.

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 in the cooldown of the installation. In addition, the process engineers of the CMS cryoplant have worked on the simulator and their conclusion is that the simulator behaviour is really close to the real plant.

The next steps in this project include :

- Operation training by creating degraded operations in simulation, hence the simulator will allow to form operators more efficient and able to react in case of failure.
- Study the improvements of the control system by using advanced control techniques in simulation to save energy and to improve the process behaviour in case of disturbances.
- The simulation of larger installations used on the LHC accelerator : the 18kW at 4.5K refrigerators, the 2.4kW at 1.8K refrigeration units and superconducting magnets of the accelerator.

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