CONTROLS OPTIMIZATION FOR ENERGY EFFICIENT COOLING AND VENTILATION AT CERN

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Abstract

Cooling and air conditioning systems play a vital role for the operation of the accelerators and experimental complex of the European Organization for Nuclear Research (CERN). Without them, critical accelerator machinery would not operate reliably as many machines require a fine controlled thermodynamic environment. These operation conditions come with a significant energy consumption: about 12 % (75 GWh) of electricity consumed by the Large Hadron Collider (LHC) during a regular run period is devoted to cooling and air conditioning. To align with global CERN objectives of minimizing its impact on the environment, the Cooling and Ventilation (CV) group, within the Engineering Department (EN), has been developing several initiatives focused on energy savings. A particular effort is led by the automation and controls section which has been looking at how regulation strategies can be optimized without requiring costly hardware changes. This paper addresses projects of this nature, by presenting their methodology and results achieved to date. Some of them are particularly promising, as real measurements revealed that electricity consumption was more than halved after implementation. Due to the pertinence of this effort in the current context of energy crisis, the paper also draws a careful reflection on how it is planned to be further pursued to provide more energy-efficient cooling and ventilation services at CERN.

INTRODUCTION

The European Organization for Nuclear Research (CERN) stands as a global leader in scientific research, known for its groundbreaking experiments in particle physics. At the heart of CERN's ambitious pursuits lie massive accelerators and experimental facilities, where the quest for scientific discovery demands precision and reliability. Among the critical components that enable these endeavors, cooling and air conditioning systems play an indispensable role, creating and maintaining finely controlled thermodynamic environments necessary for the functioning of advanced accelerator machinery. However, this necessity comes at a substantial electricity consumption: 12 % of energy consumed by the Large Hadron Collider (LHC) is dedicated to cooling and air conditioning. In times marked by growing environmental consciousness and energy rising costs, mitigating this significant energy footprint is paramount to aligning CERN's operations with its broader objectives. In a report issued in 2021, CERN's management has openly declared its ambition "to establish itself as the model for transparent and environmentally responsible research organisations", which compromises pursuing "actions and technologies aiming at energy saving and reuse" [1].

In this context, the Cooling and Ventilation (CV) group, of CERN's engineering department (EN), has embarked on a series of strategic initiatives aimed at realizing substantial energy savings within its domain. These initiatives range from energy-efficient mechanical design considerations, maintenance and operation practices, as well as automation and controls strategies that seek reducing the systems' energy footprint while preserving the demanding performance requirements. This paper particularly addresses controls optimization measures, by exposing the methodology used, project examples and results achieved to date.

The paper starts by exposing a general perspective on energy saving approaches for cooling and ventilation plants. After, the controls optimization method is introduced, and two application examples of this method in the context of energy savings are discussed. A summary of the work motivation, main results, and light on future work are provided at the end.

ENERGY SAVING MEASURES

Effective efforts for energy-efficient cooling can be addressed at several stages of a plant's life cycle. For new systems, early design considerations accounting for the energy footprint of the future plant are of paramount importance. To assist design and project engineers on this process, energy standards and regulatory frameworks can be used. Such reference documents, often created and regularly updated by professional associations with expertise in the domain - see, for instance, ASHRAE Standard 90.1 [2] - expose the best practices in terms of design, equipment selection, control and operations of the system with energy cost in view. Equally important is the realistic definition of performance requirements, which are the main driver for the plant design. The use of conservative requirements is a common practice in the sector, and this often resolves in the installation of over-sized systems that are unnecessarily energy intensive.

During the operating phase of the plant, proper maintenance and parametrization are key for a good energetic performance. An effective maintenance plan shall aim at preserving the plant's operational performance anticipated during the design phase and verified during its commissioning. As an example, increase of the pumping power is observed when plate heat-exchangers are not cleaned regularly.

Operating a plant also includes adjusting the working parameters - such as temperature or pressure set-points - according to the time-dependent user needs. It is imperative to define these parameters based on the most objective re-

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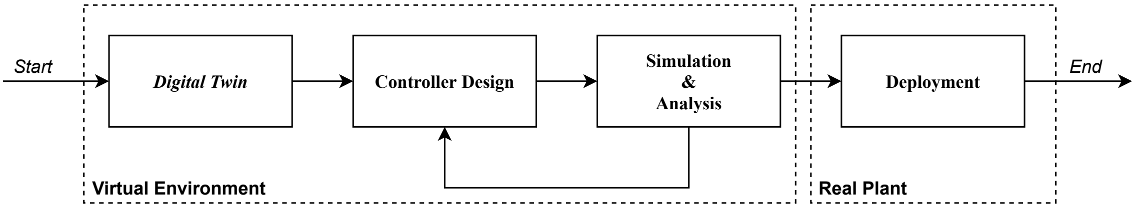

Figure 1: Controls Optimization Method.

quirements and monitor them continuously to ensure energy is not consumed excessively.

Finally, the optimization of regulation strategies used by the plant's automatic control system is also a major element to enable energy-efficient operation. Complex industrial cooling and ventilation plants can achieve their operational requirements using more or less energy, depending on how the control system acts on the several actuators at its disposal. Controls optimization is usually seen as a very cost-effective measure for energy savings given the relative low investment required. For most cases, modifications lie only at the software level and don't require costly mechanical or electrical conversions in the plants.

CONTROLS OPTIMIZATION METHOD

Over the last decade, several initiatives for energy savings using controls optimization have received the attention from the CV team. A significant example of this effort was the introduction of the economizer mode[1] in the standard controls logic of heating, ventilation and air conditioning (HVAC) plants at CERN. In addition, a smart algorithm was also introduced to automatically adjust the zone ambient temperature along an admissible range in an effort to find the most economic configuration of the plant at each point in time.

In order to continuously improve our work, the team has recently introduced the Controls Optimization Method. This new approach seeks to systematize and provide a safe platform to introduce new control strategies. The method is composed by four main stages with actions both at the virtual and real environment levels, as depicted in Fig. 1.

Digital Twin

The workflow begins with the development of a virtual replication of the plant, commonly known as the *Digital Twin*. This replica, usually integrated into a simulation software, depicts the plant's physical relationships and allows simulating its behavior under arbitrary conditions. The main ingredients to develop a digital twin is the design documentation of the plant, comprising the process and instrumentation diagram and equipment datasheets. Flow and heat-transfer simulation software (e.g. [3] or [4]) can significantly aid in the digital twin creation. These programs come with pre-built libraries containing components that emulate the most commonly used equipment in cooling and ventilation systems.

One remarkable challenge of this phase is to develop a digital twin that reliably matches the real plant, since these are usually complex and subject to unknown uncertainties. This can be, however, tackled with appropriate techniques, such as model fitting using historical process data. If process data is not available, one must rely on performance data provided by the suppliers of the equipment.

It shall be stressed that modelling a system generally requires a significant effort by the control engineers and, in general, it can not be skipped. However, often it occurs that conclusions can be fairly extrapolated from the digital twin of similar plants.

Controller Design

In a second step, the control engineer shall develop one or more proposals for the plant's control strategy. The control strategy, besides tracking the set-points of defined controlled variables (e.g. pressure, temperature, relative humidity), can be optimized for a given objective, such as the minimization of the energy consumption by the plant. Controller designs can be very diverse: from classical feedback controller, as the well-know PID (Proportion-Integrative-Derivative) controller, to advanced model-based controllers, such as MPC (Model Predictive Controller). The controller design is often an iterative process, as illustrated in Fig. 1 and discussed in the following paragraph.

Simulation & Analysis

This stage is devoted to the testing of the controller designs with the digital twin. All controllers proposed shall be tested for an appropriate set of working conditions, which must be as similar as possible to what the system will face in real life. Depending on the results obtained, the control engineer may decide to tweak, or even restart, the controller design. The final choice of the controller is backed by a performance analysis considering both the regulation variables and the optimization objective.

Deployment

In this final stage, the selected controller design shall be deployed in the industrial control system of the real plant. Depending on the scope and criticality of the project, the control engineer may decide to run a pilot test in a less critical plant. Often, this phase requires the preparation of several items comprised in the usual development workflow of an industrial control system: specification, code development, testing and training of operators. Following the deployment,

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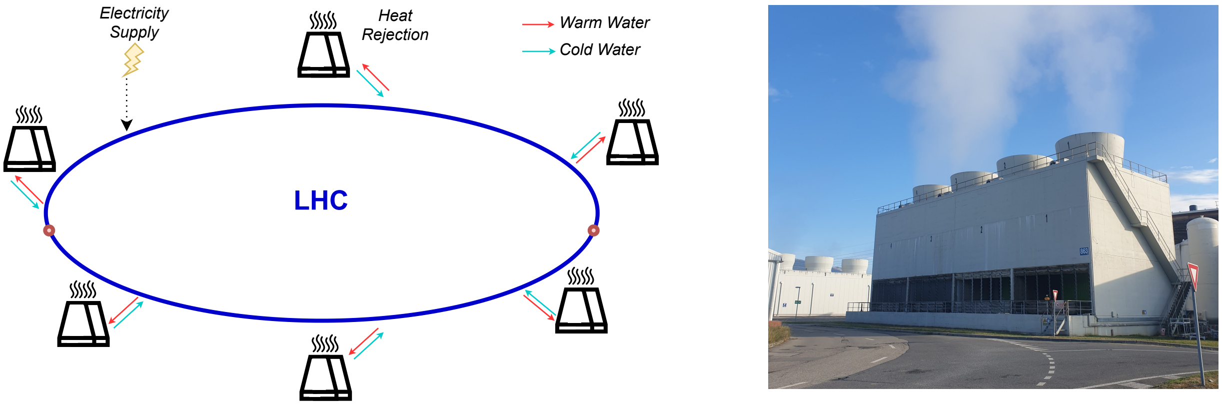
[1] Often referred as *free-cooling*.



(a) Heat rejection of LHC through 6 cooling tower plants. (b) Example of cooling tower plant at CERN.

Figure 2: LHC Cooling Towers.

the team shall supervise the plant performance and ensure that it follows the expected behavior.

PROJECT EXAMPLE 1 LHC COOLING TOWERS

Context

There are six cooling tower plants which are geographically distributed along the LHC - see Fig. 2a. Each of these is composed by a group of cooling towers (two to six, depending on the location), as in the example in Fig. 2b. These critical plants, which operate identically, are the ultimate responsible for the extraction of the heat generated by the accelerator systems within a long water-based cooling chain. The heat dissipation process takes place by the exchange of heat between water and atmospheric air. The cooling capacity of these plants is modulated by its control system, which adjusts the speed of the fans to increase or decrease the airflow through the cooling towers.

Cooling towers are an energy intensive equipment. As an example, in 2018, the six plants together required about 5100 MWh of electricity just for ventilation power. This is equivalent to the yearly electricity consumption of about 1400 European households according to data from 2019 [5].

Motivated by potential energy savings and other operational improvements required in the system, the EN-CV group decided to launch a detailed study using the controls optimization method.

Method

The project started by revisiting a digital twin model of one of the LHC cooling tower plants which was previously developed for a research project [6]. With the plant model available, the project proceeded with the proposal of four new controller designs, which were simulated and compared in detail. The one rendering the best results, in terms of outlet temperature regulation performance and energy savings, was selected for deployment in the control system of a pilot plant. Having validated the results from the pilot, the remaining five systems were gradually updated during 2020.

New Controller

As mentioned earlier, the heat exchanging capacity of the plant shall be modulated in order to cope with the dynamic cooling needs of the accelerator. In brief, this is achieved by the regulation of the outlet water temperature by adjusting two control variables:

- Staging of ventilators
- Speed of running ventilators to adjust air-flow rate

The former control algorithm followed a staging approach which consisted in progressively adapting the speed of the last started ventilator, while the one (or ones) started before were at full speed. Knowing that the power consumed by the ventilators is proportional to the cube of its speed, the system was unnecessarily energy intensive in many working conditions. During this project, it was actually verified through the digital twin that, under certain conditions, more operating ventilators at averaged reduced speeds resulted in a higher cooling capacity and decreased energy consumption when compared to running fewer ventilators at higher average speeds. The new strategy proposed aims at identifying the best combination between the number of running ventilators and their speed to match the cooling capacity required and minimum energy consumption, while guaranteeing a fine controlled outlet water temperature. A simplified illustration of the controllers' logic difference is provided in Fig. 3.

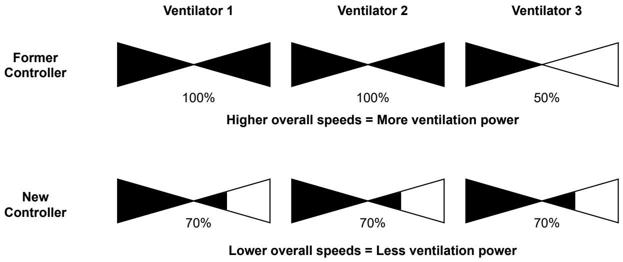


Figure 3: Illustration of difference in the staging logic between former and new controllers of LHC cooling towers.

Results

Since the deployment of the new control algorithm in 2020, it has been possible to measure and compare the resulting coefficient of performance (COP[2]) of the new and former controller versions. Table 1, which aggregates results from the six plants concerned, provides the measured energy and COP between 2017 and 2023, as well as a projection of the electricity and cost savings[3] if the new controller design was used since the first year of the analysis period. It is concluded that the new controller leads to more than a 50 % reduction in energy consumption during the operational periods of LHC.

PROJECT EXAMPLE 2
WATER DISTRIBUTION NETWORKS

Context

Pump speed regulation is a recurrent topic within the scope of CV plants. Typically, hydronic systems are equipped with variable speed pumps to supply water at a given pressure condition in a determined point of a closed-loop circuit.

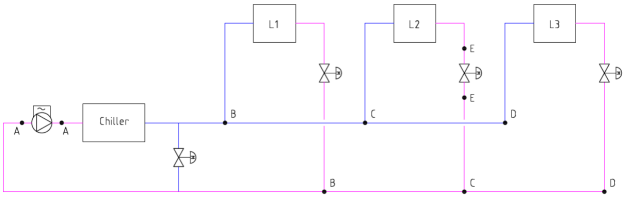


Figure 4: Example of a chilled water circuit diagram serving three users (L1, L2, L3) (source: [8]).

A common architecture of a water distribution system is depicted in Fig. 4. In this example, a variable speed pump is used to supply chilled water to three different users, each equipped with an independently-managed control valve. Commonly, in a system as the one depicted, the pump is controlled to sustain a constant differential pressure (ΔP) year-round, across points AA. This ensures flow availability for all clients under the most demanding circumstances. As one might assume, the needs for chilled water often fluctuate throughout the year. For example, air-handling units used for air conditioning generally require more chilled water during the summer months than during the winter months. At CERN, these fluctuations are also observed according to the accelerators' operation schedule. As a result, during the frequent part-load scenarios, users are required to throttle their control valves while the main distribution pump is continuously sustaining a high constant ΔP. A pertinent analogy in everyday life would be to ride a bike with a continuous high pedaling effort and using the brakes to throttle its speed. The observation of such inefficiencies was the trigger for a study (see [8]) within the CV group during 2020/2021.

Method

The control optimization process was also applied to this project. Initially, a digital twin for a generic chilled water distribution system was created using Flownex ® [4]. After, a new PID based controller was proposed and modelled within the same simulation environment as the plant. This was followed by the selection of a pilot plant to deploy and test the solution validated on the virtual environment.

New Controller

The new controller design proposed - depicted in Fig. 5 - attempts to improve the energy efficiency while not jeopardizing the level of performance and availability required. In fact, it uses the very simple idea of dynamically adjusting the ΔP set-point of the former controller PID ("PID 1" in the figure) according to the flow needs of the users. In the proposed approach, the instantaneous flow requirement of each user is perceived from the position of their regulation valves. The dynamic adjustment of the ΔP set-point is then implemented by adding an outer loop PID ("PID 2" in the figure) which uses as measured value the maximum valve opening (range 0 % to 100 %) across all users.

Results

The new controller design was commissioned in a small-scale pilot plant before the summer of 2021. Following the tests and comparison protocol, the new strategy revealed electricity savings of about 75 % under the specific load schedule of the chosen pilot plant. As for the performance and availability, no quality decrease was observed when compared to the former controller.

CONCLUSION

Beyond its ambitious scientific program, CERN has openly declared the ambition to limit the environmental impact of its activities and become a model for environmentally responsible research [1]. Aligned with organization goals, the EN-CV group has embarked on a series of strategic initiatives for energy savings in its plants. In particular, the controls team of the group has been looking over the past years at how the optimization of controls logic can be a major contributor to this end.

By introducing the controls optimization method, the team has developed a systematic and safe procedure to test and deploy innovative control algorithms. This iterative method is composed by four steps: digital twin creation, controller design, simulation and analysis, and deployment. A recognized advantage of this method for energy savings is that it results in a high return on investment, as costly hardware or electrical modifications are usually not required.

The paper discusses two important projects in which the optimization method was applied. The first project regards the cooling tower plants of the LHC for which an improved control logic was developed. The outcome of this project was the projection of 2800 MWh yearly savings during run periods of the LHC - equivalent €400k bill reduction based

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[2] Ratio between heat load rejected by the cooling towers to the electricity supplied to the ventilators.

[3] Electricity cost considered was 145€/MWh, per mean european price in the second semester of 2021 for non-household consumers [7]

Table 1: Yearly Energy Measured and Projected Savings with New Controller Design for the Cooling Tower Plants of the LHC, Based on Data from 2017 to 2023

Year	**LHC Status**	**Controller**	**Heat Rejection (GWh)**	**Electricity Consumption (MWh)**	**COP**	**Potential Electricity Savings (MWh)**	**Potential Cost Savings (k€)**
2017	Run	Former	503	4839	104	2772 (–57 %)	400,6
2018	Run	Former	542	5114	106	2889 (–57 %)	417,4
2019	Maintenance	Former	152	1316	116	690 (–52 %)	99,8
2020	Maintenance	Former/New (migration)	140	1074	130	500 (–47 %)	72,3
2021	Pre-Run	New	385	1465	262	—	—
2022	Run	New	532	2185	243	— –	—
2023 (until 30th 2023)	Run	New	376	1677	224	—	—

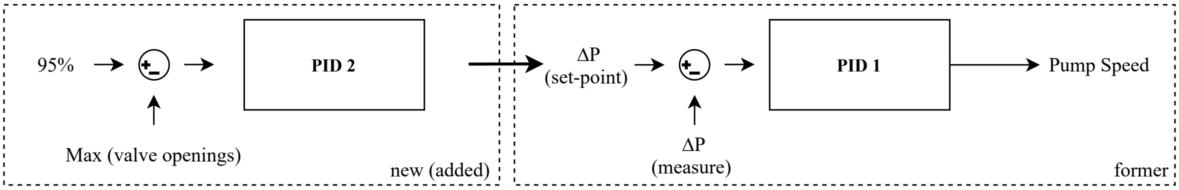

Figure 5: New and former controller designs for pump speed regulation.

on average electricity costs in Europe in 2021. The second project focused on the optimization of pump speed regulation for water distribution circuits. By following the introduced method and deploying the new solution, electricity savings of about 75 % were measured in a selected pilot-plant.

FUTURE WORK

The control optimization method has shown its benefits, but the potential it holds is far from being fully exploited within the group. These days, the team is making a particular effort to identify new plants for which the optimized pump speed regulation can be applied. These efforts concern systems that are major contributors to the energy consumed by the group and is partially driven by a partnership with an industrial player specialized on electrical motors operation and monitoring [9]. On another level, the team is engaging on key academic collaborations to explore the domain of advanced control techniques, such as model predictive control (MPC). One of these collaborations addressing HVAC plants [10] has just entered the pilot deployment phase and preliminary results are expected in the upcoming weeks.

In parallel with initiatives sustained on the design of new control algorithms, the team is also seeking measures that require very low effort but hold the potential for significant savings. As an example, the group engaged in discussions to identify plants which can be stopped during periods of decreased or no usage (e.g. air-conditioning of workshops outside working hours). This, of course, has to come with appropriate tools for convenient and efficient configuration by site operators. Finally, a further proposal for discussion is to consider how automatic monitoring tools may aid operators in maintaining energy-efficient plant parameterization, specifically the set-points of regulation loops.

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