The Future of Gas Turbine Technology
9th International Gas Turbine Conference
10-11 October 2018, Brussels, Belgium

Paper ID Number: 59-IGTC18

INTELLIGENT PREDICTIVE CONTROL OF A PUMP-HEAT COMBINED CYCLE: INTRODUCTION AND FIRST RESULTS

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ABSTRACT

The main objective of the PUMP-HEAT H2020 project is the Development of an integrated, flexibility-oriented Combined Cycle Balance of Plant concept, the PUMP-HEAT Combined Cycle (PHCC). This innovative plant layout is based on the integration of heat pumps and thermal energy storage, to un-tap combined cycle potential flexibility through low-CAPEX balance of plant innovations. In order to assess the added value of using thermal energy storage in the combined cycle, different layouts will be defined at the early stage of PUMP-HEAT. Some will include cold, warm or even hot thermal storage and some will include the latest phase change material (PCM) technologies. To manage this kind of plant, a control algorithm to achieve the best thermo-economic performances considering market requirements, plant efficiency, thermal storage level and operational constraints is mandatory. For this reason, project partners are investigating and developing different control algorithms for the PHCC integrated systems, focusing on flexibility enhancement and power grid operability. Within this framework, Model Predictive Control (MPC) algorithm for real-time supervision and management of the PHCC is being investigating and will be prototyped, virtually tested at simulation level, verified in hardware-in-the-loop and implemented in the demonstration site. The purpose of this paper is to introduce the global objectives of the project and to give details of control approaches, as well as to present the first results.

INTRODUCTION

The flexibility of power plants is a particular issue in nowadays energy production environment. The incoming of renewable sources dramatically enforces the number of daily startups and load variations of power plants. The case of Iberian Penninsula as exposed by Kries et al. (2016) is no longer the unique environment where the share of the renewable has a strong impact on energy generation. Similar problems emerged in Italy, as reported by local energy authority (ARERA, 2016) and in other EU countries as exposed by de Groot et al. (2017). A more generic review focuses on consequences for power plant flexibility is proposed by Gonzalez-Salazar et al. (2018). Furthermore, the strong influence of ambient conditions on the GTCC is another key variable. A complete analysis is exposed by Arrieta and Lora (2005). GTCC are expected to operate in severe condition in a near future. To enhance the flexibility of current power plants, it is possible to consider different options and a parametric analysis operated by Hentschel et al. (2016) shows their economic impact. To cooldown or heat up the compressor intake would be a common practice in a future – also due to emerging markets in hot region such Middle East or Africa. In literature the number of scientific works focused on this topic has been increasing and recently analyzed by Arrieta and Lora (2005), Al-Fahed et. al (2009), Baakeem et al. (2018). This means that new hardware is required. In such context, advanced control and management technique should be considered to better manage such complex system. In terms of flexibility, current power plant may undergo several unbalances (i.e. mismatch in power production against the quote of energy previously sold) due to boundary and external conditions. An example is given by variation of ambient conditions with respect to what was forecast the day ahead: at full load this may give deviations from the energy sold in the day ahead market. Another example is given by the grid frequency control, which may drive the system to compensate for energy production at zonal level – and then deviating from the production program. In PUMP-HEAT EU project a configuration of fast-cycling heat pump (HP) coupled with a cogenerative gas turbine combined cycle (GTCC) is proposed. The integration gives light to the so-called PHCC, with the following goals:

- reduce of the minimum environmental load (MEL)
- increase power ramp rates
- enable power augmentation at full load

Within the project, two main layouts will be investigated: the power oriented (PO) and the cogenerative. In the first case the plant is devoted to produce electrical energy only. The HP is used to perform inlet conditioning at the compressor intake. The aim of HP is then to extend the range of operability during the different operating conditions. These are peak and off-peak conditions and are linked to the current status of the market (Figure 2), as explained by Giugno et al. (2018). In this configuration an interaction between the two systems and cold storage (5°C) is defined. Considering the operation in cogenerative mode, these goals are achievable by exploiting the effect of HP on the GTCC plant, coupled with a hot thermal storage (120°C). The level of the temperature is however linked to the temperature persisting in the district heating network (DHN), which may allow for the installation of a warm storage (70/90°C). Considering a generic HP with COP=2.5, the extension of the MEL is made possible considering figure 3. In the project, the cogenerative configuration will be tested and implemented at TRL 6 in the demonstration site located in Turin (Italy) on the Moncalieri 400 MW GTCC. The plant is equipped with a Siemens V94.3A with annular combustion chamber. The plant can operate into full electric or cogenerative configuration. In this second configuration, the electric power drops to 360 MW while producing 260 MW of thermal energy. Current estimations on advantages of such integration will allow a yearly saving of 5000t of natural gas and 72000 tCO_2 eq.

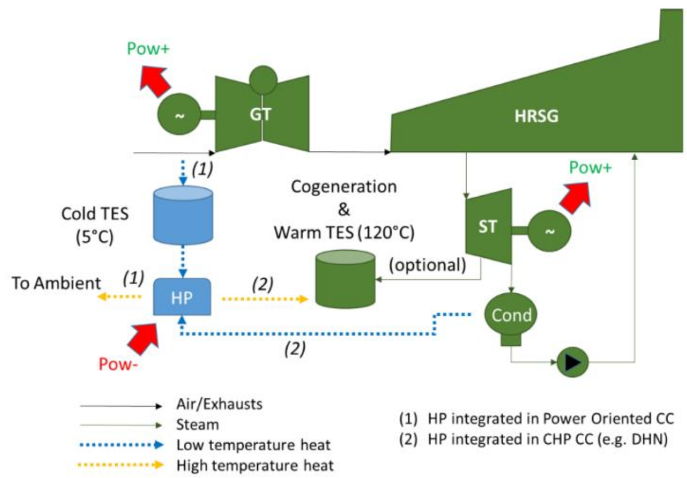
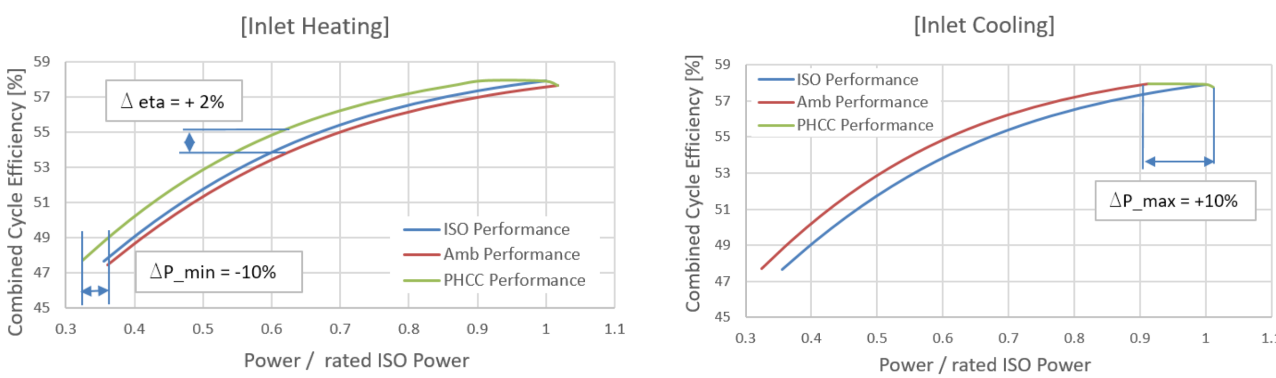


Figure 1 – Scheme of PHCC in PO (path 1) and cogenerative (path 2) configuration



(a) (b)

Figure 2 – PHCC in PO configuration: a) Inlet heating during off-peak and b) Inlet cooling during peak

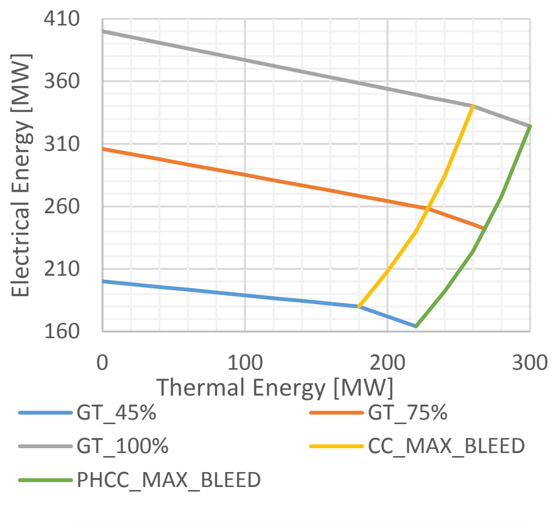


Figure 3 – PHCC in cogenerative configuration: a) Operational range and b) Performance

The control and management of such complex power plant will be held by a predictive controller where current scheduling, constraints and plant status will interact to define the best control action. The controller will be developed in Matlab/Simulink and will be interfaced with the model of the plant developed in Amesim. The duo will be interfaced in software-in-the-loop configuration. This process will refine and test the reliability of control logics. The output of this procedure will be implemented in hardware and implemented in the test rigs. The control will govern the heat pump in face of GTCC behviour. The testing of the PO configuration will be held at the UNIGE facility. This is based on a GTCC emulator. The emulator will be formed by the AEN T100 microgas turbine – a 100kW cogenerative engine based on a recovered cycle. This revolves at 70000rpm for 0.8 kg/s of evolving air. The engine will be coupled with a bottoming cycle model running in real time – in this way a GTCC is emulated – similarly to what was done by Ferrari et al. (2016) for SOFC/Gas Turbine hybrid systems. The timeline of the project schedules the emulator to be reedy at the beginning of 2019, followed by the Moncalieri plant. At this stage, the involved partners carry out the modelling and development of control logics. This paper exposes the methodology adopted to face the control problem. Firstly, the approach to the modelling is presented, then adopted control logics and hardware implementation are described.

NOMENCLATURE

Acronyms	
AP	High Pressure
COP	Coefficient of Performance
DCS	Digital Control System
DHN	District Heating Network
GTCC	Gas Turbine Combined Cycle
HP	Heat Pump
HRSG	Heat Recovery Steam Generator
IP	Intermediate Pressure
LP	Low Pressure
MEL	Minimum Environmental Load
MPC	Model Predictive Control
PCM	Phase Change Material
PHCC	PUMP-HEAT Combined Cycle
PO	Power Oriented configurairion
Symbols	
b	Constraints matrix
h	Specific enthalpy
P	Power [MW]
p	Absolut pressure
Q,R	Weighting matrices
s	Specific entropy
T	Temperature
u, η	Control variable

MODEL DESCRIPTION

To support the development of the control system, a model representing the investigated plant is required. This will be integrated in the loop with the predictive controller for testing the logics. The virtual representation of the power plant with combined cycle is needed for the MPC to correctly predict the impact of each potential action. The power plant includes many different closed or open thermodynamic systems:

- The natural gas turbine system
- The water steam cycle system
- The thermal storage system
- The District Heating Network
- The river water
- A Heat Pump

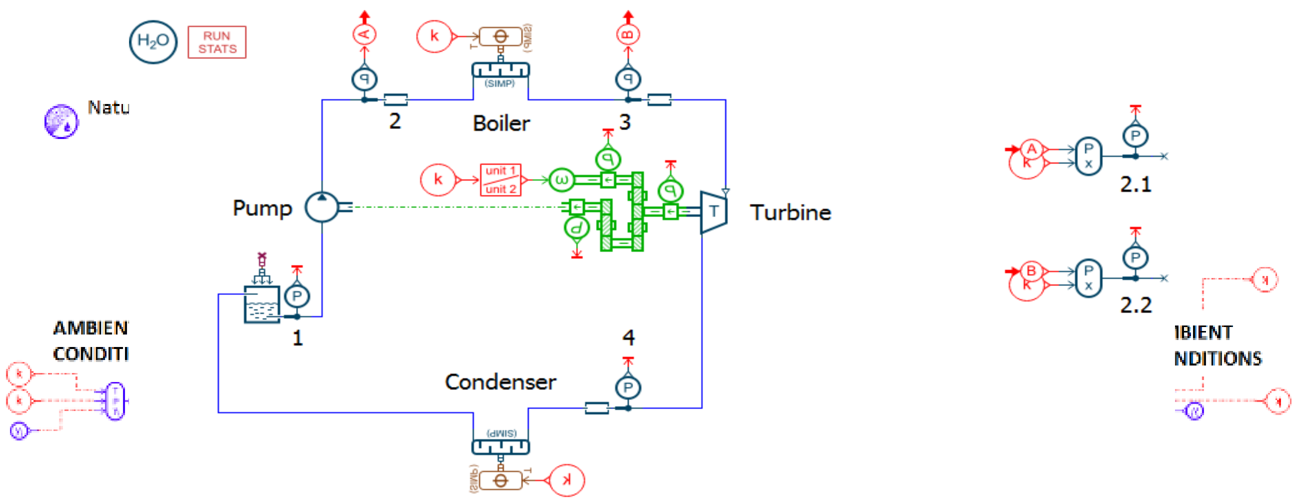


Figure 5 – Simcenter Amesim model of the simplified power plant steam cycle

The model will be developed using the system simulation software Simcenter Amesim. The need is to describe the transient behavior of these subsystems and the interactions between them. Using a scalable approach, the proper level of detailed is chosen for modeling each subsystem in order to get a virtual plant which is predictive enough and fast enough to be used by the control logic on the chosen hardware. A brief description of single subsystem composing the PHCC model is then presented.

The gas turbine system

The natural gas turbine system involves several physical phenomena including

- The compression of the air
- The fuel injection and mixing
- The heat generation, thermodynamic chemical composition changes due to combustion
- The mechanical power generation in the turbine
- The heat exchange in the HRSG

Using 1D simulation, the gas turbine engine library of Simcenter Amesim is used. Each phenomenon becomes a specific component with its own inputs, outputs, parameters and internal laws. Figure 4 shows the Simcenter Amesim virtual system for a GT system, with compressor, combustor, turbine and generator.

The steam cycle system

The water steam cycle involves several physical phenomena including

- The phase change input heat in the HRSG (boiler)
- The mechanical power generation in the turbine
- The High Pressure (AP), Intermediate Pressure (IP) and Low Pressure (LP) turbines
- The heat release to the District Heating Network (DHN) via a heat exchanger
- The phase change and heat release to the river via a heat exchanger (condenser)
- Several pumps

In a first level approach, the cycle has been simplified to a one stage steam cycle. Figure 5 shows this model in Simcenter Amesim. The water properties are defined based on a standard definition from the National Institute of

Standard and Technologies (NIST). This definition is using a Helmoltz formalism of the equation of state.

The thermal storage system

The thermal energy storage is based on Phase Change Material (PCM) tehnology. Based on recent development in Simcenter Amesim, the latent heat storage can be modeled with a dynamic calculation of the solid mass fraction and specific enthalpy.

The District Heating Network (DHN)

The global DHN is not modeled. The key for the PUMP HEAT project is heat exchange between the DHN and the steam cycle, rather than a complete model of the DHN. Therefore, a boundary condition at this heat exchanger will be considered.

The river water

The river is an infinite source of cold water flow for the system and therefore a boundary condition at the condenser.

A Heat Pump

PUMP HEAT project, will require a heat pump for the energy flow to be controlled between the thermal energy storage and other subsystems, depending on the investigated configuration. In the virtual plant a simple control law is used and further detailed upon need.

Global model

All these subsystems are combined into one unique model for each layout. In this virtual plant, the direct and transient impact of each decision taken by the controller will be evaluated and returned to the control logic.

CONTROL LOGICS

The development of the control undergoes several parallel steps. In the PHCC environment, a multi-variable constrained problem must be faced. The main problem the controller has to face is basically the reduction of power unbalances, as well as governing properly the PHCC plant while operating in grid frequency control. In the PHCC framework, the GTCC sells the energy the day ahead and in this decision process, the working conditions of the HP are set. Once the operating programming for energy production is not respected in real time operations, an unbalance occurs. The unbalances are computed by the grid distribution company for fixed time windows of 15 minute. Therefore, to minimize the unbalance, it is necessary to maintain a fixed window over which the system is monitored and governed.

At each time-step, the controller must govern properly the HP considering the information derived from the current status of the GTCC while monitoring the storages interaction with the system. In particular, the controller must be able to predict the status of the stored energy at a certain time while considering the available loading ramp of the HP – and maintain the whole system into safety operating conditions. At the same time, the control system must be aware of production links between HP and GTCC. In case of inlet cooling for example the effects can be noticed minutes after the action is taken. In this case a moving time window is requested as it is necessary to understand at each time step which would be the consequences in future minutes on the GTCC. This is independent from unblances evaluations and reduction. There is then the need to find out a tradeoff between unbalance reduction and robustness.

The control problem is not anyway enclosed in the management of the HP but it must considers also the different situations in which the power plant is operating. The possibility for continuous cooling, storage charging and discharging or simple operations obliges the controller to operate several choices.

The control logic moves through different states, on the basis of the current plant situation and boundary conditions. This is dependent on the storage status, condition required at engine inlet etc. This is the high level control – which is mainly based on direct feedforward and simple control loops. Once the switch from different status occurs, pumps and valves must be activated. A lower level predictive control governs the HP on the basis of the current plant status – and this is a hierarchical MPC. The information coming to the MPC are pre-defined: the plant energy has been already sold on the market the day before and the CC and the HP are planned. In particular, the HP planned production will be delivered with some associated operational margin. Typical situation may occur once electric price is very low and the HP runs at maximum power without any margin from its setpoint. This margin in power is available every 15 minutes. In those conditions where the margin is zero, the MPC tracks the requests. When the margin to intervene is available, the MPC may operate on the HP with the goal to minimize the unbalances at the end of the 15th minute. Therefore, the model embedded must include the constraints on the storage and its current status, as well as influence of HP on the GTCC – together with a transfer function representing the HP and its main time constant. The predicting horizon of the MPC is a moving 15 minutes horizon. An outsider function therefore must take into account the current unbalance within the current interval – and considering the power margin gives the input to MPC.

In the end there are two different levels

a first one working at constant time windows 15 minutes long, where unbalances are minimized. This gives input to MPC

a second one, that is, the MPC itself where a moving horizon of 15 minutes consider the constraints and the operating influence of HP on the GTCC – and so the control action is obtained and implemented.

The hierarchical MPC is then governed by a supervisor which held the decisions for moving from one condition to another one on the basis of the output coming from the plant and on the basis of the boundary conditions (i.e. ambient temperature, cost of electricity, status of GTCC). Figure 6 shows a summary of the management and control practice that is going to be developed within PUMP-HEAT project. MPC is a model-based control system where a plant model is used to forecast plant status along a moving predicting window – and control outputs are obtained by minimizing a cost function.

In this project, the MPC architecture is based on velocity form as presented by Wang and Young (2005). The model developed for the control is based on augmented state-space representation, i.e. Non-Minimal State Space (NMSS) (eq.1) (see Wang and Young, 2005). The identification of the NMSS will be based on time constant for the HP, transfer functions representing the GTCC and pumps, while simple integrators will represent the storages.

$$\begin{vmatrix} \Delta x_m(k+1) \\ y(k+1) \end{vmatrix} = \begin{vmatrix} A_m & 0_p^T \\ C_m A_m & 1 \end{vmatrix} \begin{vmatrix} \Delta x_m(k) \\ y(k) \end{vmatrix} + \begin{vmatrix} B_m \\ C_m B_m \end{vmatrix} \Delta u(k \quad 1)$$

$$y(k) = |0_m \quad 1| \begin{vmatrix} \Delta x_m(k) \\ y(k) \end{vmatrix}$$

This non-minimal representation is detectable and stabilizable if the original model is detectable and stabilizable and has no transmission zeros on the unit circle. This NMSS is integrated within a MPC derived using Laguerre network. Briefly, Laguerre network is used to simplify DMPC computation by adding tunable parameters. In literature, Laguerre functions were used to describe the pulse response of dynamic systems. Therefore, through Laguerre network it is possible to describe dynamic behavior of target system. In DMPC, ΔU control sequence it is composed by the Δu(ki+Nc-1) terms of the control horizon, that is, a discrete polynomial function.

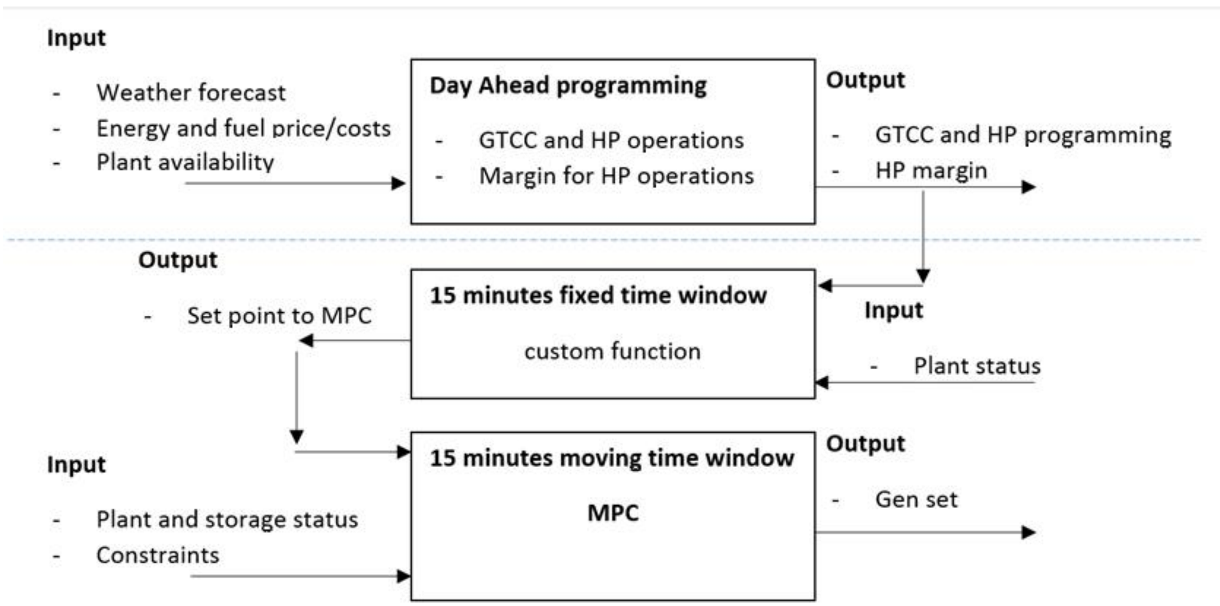


Figure 6 – Scheme of control logics

As consequence, this could be represented by Laguerre network. In this regard, there is no a priori definition for Laguerre's parameter, but in general a vector N, which size corresponds to the number of inputs, determines the number of Laguerre network.

One of the advantages of MPC is linked to possibility to tune controller response based on weights associated to control variables. Here, cost function is based on Discrete Linear Quadratic Regulator (DLQR) architectures, that are used to be as equation 2, with Q and R weight matrices.

$$J = \frac{1}{2}x^T Q x + u^T R u \tag{2}$$

Of course it is possible to intervene on the single values of the Q,R matrices, in order to regulate precisely the desired control variable of system output. Q has non negative elements on the final term of the diagonal. These are the elements that could be modified. R is diagonal.

Once Laguerre is introduced in the loop, control variable u change in definition as it is captured within Laguerre network. As consequence, to underline this change in notation, the "new" control variable is called η. Since J has been defined previously, it is possible to demonstrate that its optimal solution could be obtained with:

$$\eta = -\Omega^{-1}\Psi x(k_i) \tag{3}$$

Where

$$\Omega = \sum_{m}^{Np} \varphi(m) Q\, \varphi(m)^T + R \qquad 4)$$

$$\Psi = \sum_{m}^{Np} \varphi(m) Q\, A^m$$

In reality this implementation must face the limitation due to the installation in the power plant. The control logics will be developed and tested at first in the PO emulator rig. Once the logics and the controller is validated, the control hardware will be installed in the Moncalieri power plant. Considering the PO, the HP must

Constraints are defined on absolute value of inputs u and their rate of change Δu. In general the constraints problem is defined as equation 5 where b is made up by constraints on u and on Δu

$$A_{cons}\eta \leq b \qquad 5)$$

influence the compressor intake and governing the power output on the basis of the plant responses. For the T100 there is a clear influence between plant performance and compressor intake temperature as demonstraited by Ferrari et al. (2016) – and on the basis of this influence the control strategy for the PO will be developed. Similarly, same work will be outlined for cogenerative test-rig.

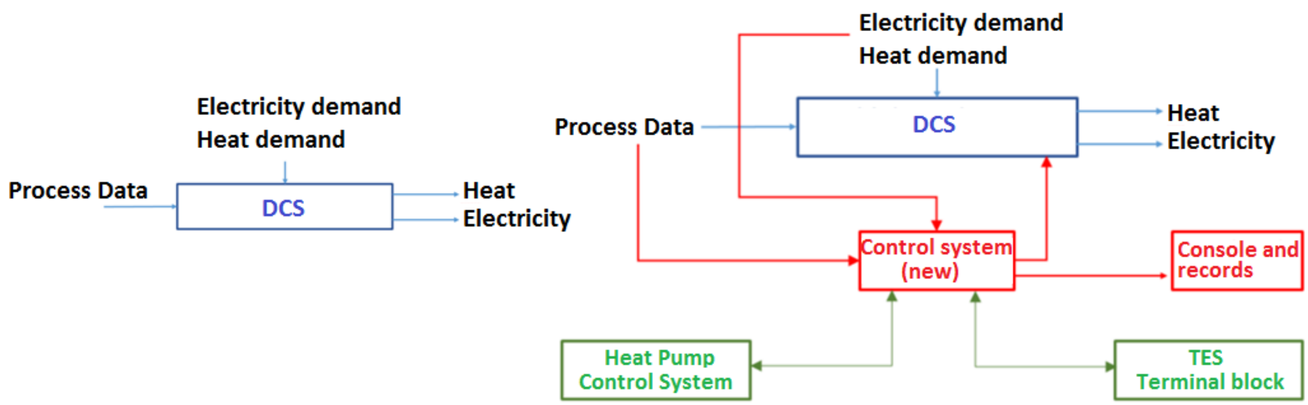


Figure 7 – Scheme of control scheme (a) as it is right now and (b) how it will be enriched within PUMP-HEAT

HARDWARE IMPLEMENTATION

Many considerations have to be taken into account to design hardware implementation:

- Interface existing plant Control Systems
- Interface new Pump Heat and the TES
- Implement the MPC Control
- Produce HMI for control of Heat Pump and TES
- Store and show results in a specific test console.

In addition, the hardware will have to be consistent with the process of the project: the algorithm will be tested “model in the loop” by UNIGE then “software in the loop” by Siemens, then implemented on NovEner Hardware and tested as “hardware in the loop” before real implementation.

All these constraints have led to choose a multi-purpose computer. It will have to integrate:

- I/O for interfaces, PLC-type
- PLC-type functions for sake of simplicity and controllability by plant automation operators
- Double Network attachment: one for interfacing other devices (Heat Pump), one for its own purpose with various devices
- Serial links if needed for other apparatus or security systems
- One CPU (or virtual machine) running scientific algorithms, with MatLab capability
- One CPU (or virtual machine) for HMI server, operational storage, Supervision firmware
- One CPU (or virtual machine) for all the test environment, storage, sequences.

All together, it may be either a hybrid computer or a set of different devices such as PCs (servers and clients) plus PLC plus available network.

Such hybrid computers exist but at the moment the capacity may be insufficient. Investigation and tests should be carried out in order to check whether it is convenient or if it is needed a complete system with various devices.

Currently, the Moncalieri plant is operated using a Digital Control System (DCS) arranged as figure 7(a). In the PHCC a TES and a HP will be installed. HP will be delivered with its own control system, while TES comes with terminal blocks where instruments are connected. Therefore a new control system interface will be developed starting from the original DCS. The proposed scheme is presented in figure 7(b). Information from process data will feed the developed control system i.e. the MPC discussed previously. The direct acquisition from PLC is not acceptable for this stage of development: an OPC UA from existing DCS is considered. It is possible to consider any other real-time protocol as well.

As explained previously, the output of the controller governs only the HP – and TES consequently. These outputs are directly sent to the two components and in no way it will be direct control of the existing DCS. As consequence, alarms for abnormal operations or conditions at HP and TES must be derived somehow else.

CONCLUSIONS

This paper presented the methodology adopted within the PUMP HEAT project to define and test the control approach that will be integrated in test rig. A PHCC model has been developing in Simcenter Amesim environment. The Gas Turbine and the Steam Cycle have been developed and tested. The model will be used to test the control logics which will be developed within Matlab/Simulink and tested in software in the loop application through a cross-software configuration. The control logic is based on a speed formulation of MPC. Once the logic has been tested, this will be implemented on a real hardware interacting with the current DCS installed. The next steps will be integrating the developed logics within the developed model and test its reliability and robustness.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 764706

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