

ТЕХНИЧКО РЕШЕЊЕ

Назив	Управљање и аутоматизација система за грејање, хлађење и вентилацију базираног на технологији топлотне пумпе са више извора
Аутори	Катарина Станковић, Марко Батић
Категорија	Ново техничко решење у фази реализације (M85) Доказ: Протокол о тестирању
Кључне речи	топлотна пумпа, обновљиви извори енергије, подно грејање, клима комора, системи за климатизацију, грејање и хлађење (eng. HVAC), управљање, систем за надзор, контролу и прикупљање података (eng. SCADA)

За кога је решење рађено (правно лице или грана привреде):

Техничко решење је рађено за потребе аутоматизације система за грејања, хлађења и вентилацију објекта у Универзитету у Ферари, Италија

Година када је решење компетирано:

2023

Година када је почело да се примењује и од кога:

Примена техничког решења почела је у 2022. години, пуштањем у рад система

Област и научна дисциплина на коју се техничко решење односи:

Техничко-технолошке науке; информационо-комуникационе технологије

Технички елаборат:

- Проблем који се техничким решењем решава
- Стање решености тог проблема у свету
- Опис техничког решења са карактеристикама, укључујући пратеће илустрације и техничке цртеже
- Референце

ТЕХНИЧКИ ЕЛАБОРАТ

Проблем који се техничким решењем решава:

Heating, ventilation and air-conditioning (HVAC) systems are an indispensable part of today's living comfort. At the same time, those systems are significant energy consumers¹, and their energy-efficient work is crucial. Since increasing their share lowers carbon dioxide emissions into the atmosphere, improves energy supply security, and reduces reliance on imports of electricity and energy raw materials, it is quite common for such systems to be integrated with non-conventional, renewable energy sources. However, when a system integrates multiple different energy sources, storage media, and consumer appliances, the task of monitoring and controlling energy flows, becomes too complicated for human operation, raising the question of how important it is to use the right software for these purposes.

The considered multi-source/sink HVAC system [1] features a non-standard reversible water-to-water heat pump (HP) integrated hybrid technology that combines three different renewable energy sources: geothermal horizontal heat exchangers (GHXs), air-to-water exchanger (AHX or a dry cooler unit), and solar electric and thermal energy sources in the form of solar collectors (PVTs), Figure 1. The heat pump operates in two primary hydronic loops between source- and user- thermal buffers, that guarantee stability and decoupled operation of source side and user side of the plant. Finally, the heating, ventilation and air-conditioning are carried out through two terminal units: radiant floor (RF) system equipped with state-of-the-art phase-change materials [2] and air-handling unit (AHU). Entire system is operated by proper actuation over circulation pumps and three-way valves installed according to the required system operability.

This multi-source heat pump (MSHP) based technology found its suitable demo-site in one of the facilities of the University of Ferrara, in Italy, which is utilized as the snack bar. Before the new technology was installed, the system had been air-conditioned using the legacy all-air system, which has been kept in place. The existing air-handling unit has been slightly modified by incorporating a new finned coil heat exchanger in addition to the original one. In that way, old and new HVAC systems maintained their hydraulic independence while still both being operational.

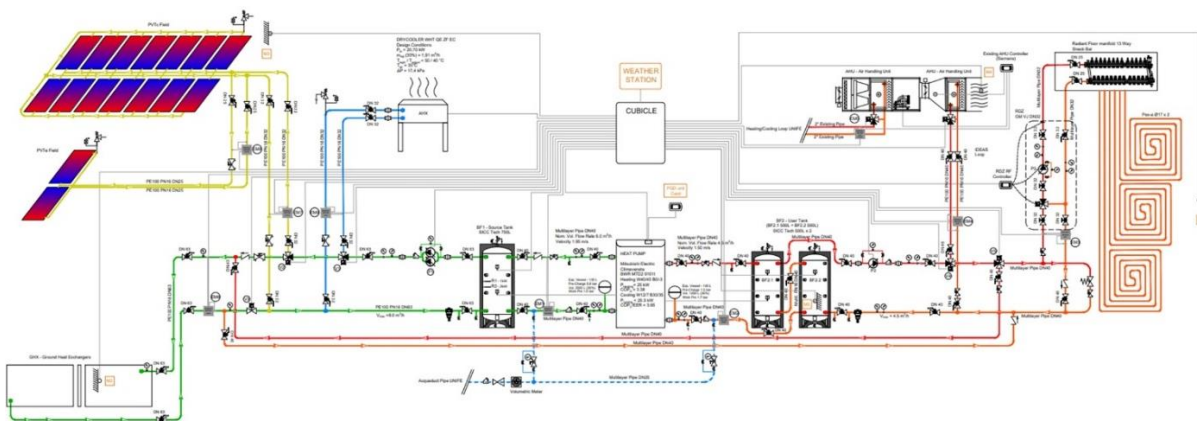


Figure 1 – Piping and instrumentation diagram of the HVAC system [3]

¹ In 2020, approximately 42% of Europe's energy consumption came from the building sector, with heating and cooling needs accounting for around half of that [4].

Стање решености тог проблема у свету:



With 10% of the space heating needs covered in 2021, HP technology has emerged as the most prominent technology in the global energy transition and electrification discourse [2][5]. Due to its widespread use in the building sector and relatively easy installation, the air-source heat pump (ASHP) is currently the most prevalent HP technology on the market. However, the air temperature outside has a significant impact on its efficiency. Additionally, the possibility of evaporator defrosting in the winter has led to the search for a more efficient option, which is the MSHP [6]. For reversible HP in heating and cooling modes, these systems can supply steady high-temperature sources or low-temperature sinks. Their reliability and energy-saving potential have been presented through several studies, but available literature mainly elaborates on simulation-based studies for optimal MSHP system and component design, while there are fewer studies based on real-world plant monitoring and control, often targeting only a specific part of the plant or small-scale lab installations [7].






Опис техничког решења са карактеристикама, укључујући пратеће илустрације и техничке цртеже:





Hardware Integration



In order to develop a control application for such a system, a comprehensive analysis of the infrastructure of the demo-site plant was conducted, with a specific emphasis on the field instrumentation technical capabilities and compatibility with the external control system for seamless integration. Thus, Table 1 contains a list of all available sensors, actuators, and heat exchangers.

Table 1 – Technical characterization of the demo-site field instrumentation

1x WEATHER STATION	
<p>Weather station, installed on the roof, close to the PVT panels. Measures both inside and outside air temperature, humidity, rain rate, wind speed and direction, solar irradiance. Means of communication: <i>Modbus TCP</i> protocol Weather station, equipped with a Modbus TCP/IP gateway</p>	
9x THERMAL ENERGY METERS	
<p>Ultrasonic thermal energy meters, equipped with two Pt100 probes installed on the inlet and outlet of a specific section. They were installed on the heat pump source side (MD01) and user side (MD02), on the radiant floor (MD03), on the new HX of the AHU (MD04), on the old HX of the AHU (MD05), on the GHX (MD06), on the commercial PVT panels (MD07), on the experimental PVT panels (MD08) and on the AHX (MD09). The way they are mounted and configured in the demo-site, they measure inlet and outlet fluid temperatures, temperature difference, actual and maximum volume flow rate, actual thermal power and thermal energy. Means of communication: <i>Mbus</i>, by utilizing Mbus/Modbus TCP converter, mounted in the control cubicle.</p>	

<p>4x THERMASGARD HFTM</p> <p>4-wired platinum RTD with a resistance of 1000 Ω at 0°C (Pt1000, class B) temperature sensors, with Modbus RS485 communication interface.</p> <p>Used to monitor the piping of the GHX (THERM_GHX), the surface of the commercial PVT panels (THERM_PVTc), the surface of the experimental panels (THERM_PVTe) and the air temperature entering the AHU (THERM_AHU).</p> <p>Means of communication: <i>Modbus RTU</i> protocol Modbus line 1 (38400 bps, 1/8/N/2)</p>	
<p>1x HYGRASGARD RFTF</p> <p>Digital humidity sensor with integrated temperature sensor, with Modbus RS485 communication interface.</p> <p>It provides the unique measurement of indoor air temperature (aside from the weather station recording) inside the Snack bar (HYDR), that temperature regulation relies on.</p> <p>Means of communication: <i>Modbus RTU</i> protocol Modbus line 1 (38400 bps, 1/8/N/2)</p>	
<p>4x 3PH ENERGY METER</p> <p>Three-phase energy meters – two accompanied to the PVT electrical box, one accompanied to the heat pump (EM_HP) and one assigned to the dry cooler (EM_AHX).</p> <p>They allow for measuring electrical active, reactive power and electrical consumption in <i>kWh</i>.</p> <p>Means of communication: <i>Modbus RTU</i> protocol Modbus line 1 (38400 bps, 1/8/N/2)</p>	
<p>5x 1PH ENERGY METER</p> <p>Single-phase energy meters – accompanied to the pump 1 (EM_P1), pump 2 (EM_P2), one accompanied to two resistors inside the source buffer (EM_Resistors), one accompanied to two boilers inside the kitchen, and one meant for the experimental PVT panels.</p> <p>They allow for measuring current, voltage, electrical power and electrical consumption in <i>kWh</i>.</p> <p>Means of communication: <i>Modbus RTU</i> protocol Modbus line 2 (9600 bps, 1/8/N/2)</p>	
<p>1x HEAT PUMP</p> <p>Water-to-water heat pump, with heating capacity of 25kW and cooling capacity of 25.3KW, equipped with two buffer tanks, on the source and user sides.</p> <p>Modbus interface allows collection of all the relevant variables, such as outlet water temperature, compressor speed, inner pumps speeds, control over the user buffer temperature, choice of the seasonality, etc.</p> <p>Means of control/communication: <i>Modbus RTU</i> protocol, Modbus line 2 (9600 bps, 1/8/N/2)</p>	

<p>1x DRY COOLER</p> <p>Air-heat exchanger, AHX, or the dry cooler, mounted on the roof, precisely, hallway roof, behind the Snack bar. It's featured by thermal capacity of 20.7kW. The fan speed controllable by means of Modbus interface, allows for AHX switching on and off. Means of control/communication: <i>Modbus RTU</i> protocol, Modbus line 1 (38400 bps, 1/8/N/2)</p>	
<p>4x THREE-WAY and 1x TWO-WAY VALVE</p> <p>Three-way proportional valves were mounted in the flow diverting/splitting configuration, two in the source side, and two in the user-side of the plant. One two-way proportional valve was mounted at the outlet of the GHX and utilized as on/off valve. Due to a Modbus interface, those actuators can provide the information about valve regulation port opening, valve bypass port opening, control via override discrete signals, for reaching maximum, medium or minimum opening position, or via set-point value. Means of control/communication: <i>Modbus RTU</i> protocol, Modbus line 1 (38400 bps, 1/8/N/1)</p>	
<p>1x TWIN CIRCULATION PUMP (speed control)</p> <p>Circulation pump P1, operating on the source side of the layout, with two heads, that can work in alternating, simultaneous or main/reserve configuration. Relative speed (frequency) control via Modbus interface. Turning on/off via communication possible too. Means of control/communication: <i>Modbus RTU</i> protocol, Modbus line 2 (9600 bps, 1/8/N/2)</p>	
<p>1x CIRCULATION PUMP (speed control)</p> <p>Circulation pump P2, operating on the user side of the layout. Relative speed (frequency) control via Modbus interface. Turning on/off via communication possible to. Means of control/communication: <i>Modbus RTU</i> protocol, Modbus line 2 (9600 bps, 1/8/N/2)</p>	
<p>1x THREE-WAY MIXING VALVE</p> <p>Three-way mixing valve installed at the inlet of AHU heat exchanger, that belongs to the new system. Proportionally controlled opening, via external voltage signal in range 0–10V. Due to the absence of feedback information regarding the regulation port opening or flow, utilized as an on/off valve. Means of control/communication: valve opening set-point controlled by the external output voltage signal, coming from the KOV module in the cubicle.</p>	

<p>1x controller of AHU legacy HEAT EXCHANGER (valve at the HX inlet)</p>	
<p>The existing AHU is controlled by a Siemens KNX controller, that actuates on the three-way mixing valve, same as the one installed as part of the new system. Means of control/communication: external output voltage signal, coming from the KOD module in the cubicle.</p>	
<p>1x RDZ</p>	
<p>RDZ represents the radiant floor controller device, that controls the pump and the three-way mixing valve in the RF control group, marked in the P&ID. It's equipped by Modbus interface, that allows for its turning on/off, adjusting the RF supply water temperature, setting the season, etc. Means of control/communication: <i>Modbus RTU</i> protocol, Modbus line 2 (9600 bps, 1/8/N/2)</p>	

Control hardware

Designed and later on commissioned supervisory control unit represents an instance of the IMP's (Institute Mihajlo Pupin) proprietary VIEW4 SCADA (Supervisory Control and Data Acquisition) system h/w and s/w technology [8][9], custom designed to be coupled with existing technologies within the equipment of pilot site plant. Whole equipment in charge of process data acquisition, and remote or local monitoring, represents RTU (Remote Terminal Unit) and completely meets the standards and requirements of the ISO / OSI reference model. Real-time control is mainly accomplished through the coupling of PLC (Programmable Logic Controller) [9] and accompanying I/O modules with the plant devices, while the central supervision belongs to the superior VIEW4 SCADA server. Engaged PLC, from Atlas Hydra family, enabled both control and reliable data collection from different devices using different communication channels and protocols (IEC 61850 Client/Server, IEC 60870-5-101 Master/Slave, IEC 60870-5-102 Master, IEC 60870-5-103 Master, IEC 60870-5-104 Client/Server, Modbus RTU and TCP Master/Slave, Modbus TCP Client/Server, NTPv4 Server/Client, etc.) and certainly allowed for monitoring and control of the previously characterized field instrumentation, Table 1. Particularly, various I/O modules (KID, KOD, KIA, KVA) were utilized for activating contactors of the devices and gathering signals from Pt100 temperature probes. Communication with the weather station was achieved via Modbus TCP, while Modbus RTU was primarily used for most other communication needs. This included interfacing with Thersmagard and Hydrasgard temperature probes (Pt1000 probes with a Modbus interface located on GHX, PVT, AHU, PVTe, and inside the snack bar's indoor space), three- and single-phase energy meters (for HP, AHX, P1, P2, source buffer resistors), PV panel energy meters, the heat pump's communication board, circulation pumps (P1 and P2), and the control box of the radiant floor. Additionally, a Mbus/Modbus TCP converter installed in the cubicle provided real-time data collection from thermal energy meters.

Control software

PLC program

The development of the customized control application and human-machine interface (HMI) was adapted to the available sensors, the controllability of the actuators, the unique requirements of the Snack bar HVAC system, and the needs of the researcher-profile user (University of Ferrara team, in charge of testing the designed hybrid technology). Several full-size screens that allow for more advanced settings and monitoring (of the automatic mode behavior, particularly), along with one

comprehensive home screen, encompass most of the tasks that an operator would perform. The level of authority granted to users depends on his/her assigned privileges, and the HMI requires user authentication for accessing the control application, with three configurations implemented (*final*, *technician* and *super user*), Figure 5. In summary, the control logic supports various functionalities, including but not limited to:

- operating in Manual, Semi-automatic and Automatic mode,
- operating in AI or Local mode,
- operating with different configurations of sources (G/A/S/GA/GS/GA UTS/GS UTS/AS PVT),
- fine-tuning of the source selection-algorithm,
- both cooling and heating operation,
- tracking the facility working time and needs for air-conditioning,
- air-conditioning with modular choice of radiant floor or/and air-handling unit engagement,
- regulation of temperature in multivariate load-sharing structure.

Eight different configurations of sources, Table 2, and three possible user-side layouts are supported. To accomplish a specific configuration or a seamless mode transition, PLC control logic was programmed to appropriately perform actuator activation/movements, by taking into account data coming from the plant peripheral measuring devices, set-points, parameters and commands entered through the HMI, as well as those coming from the cloud-based AI-driven optimization service.

Table 2 – Possible control states, or different configurations of sources

<i>CASES</i>	<i>ACRONYM</i>	<i>EXCHANGERS</i>	<i>AIM</i>
Solar source	S	PVT	Use of PVT for heating
Ground source	G	GHX	Use of GHX for heating/cooling
Air source	A	AHX	Use of AHX for heating/cooling
Ground + Air source	GA	GHX + AHX	Use of GHX & AHX for heating/cooling
Solar + Ground source	GS	GHX + PVT	Use of GHX & PVT for heating
Underground heating/cooling storage	GA UTS	GHX + AHX	Use of AHX for ground heating/cooling storage
	GS UTS	GHX + PVT	Use of PVT for ground heating storage
PVT cooling	AS PVT	AHX + PVT	Use of AHX for PVT cooling

The control of the plant's source side focuses on making optimal use of the sources that are available for thermal charging the source buffer tank (BF1), which serves as the HP system's direct source. How choice of the state will be made, depends on the previously selected level of automation. Manual is the regime that carries the lowest level of superior control and gives the highest degree of freedom to the operator, allowing him/her to set the plant, including all the actuators, freely according to his/her heuristic knowledge. Semi-Automatic mode offers the user the possibility to select among predefined modes (plant operating states: S, G, A, etc.) which are meant to be active during the current weather season. User engagement consists only of selecting the desired mode, and logic will apply the specification of that state. The information about the share of each source within the specific state is coded in a certain combination of the valve regulation ports openness. Even in the absence of explicit selection, the automatic nature of the Semi-automatic operating will retain the inherited state from Automatic or Manual mode, with existing basic automation that will take care of the actuator states properly. Automatic mode brings real automatic reasoning, by determining the most advantageous state to activate, and control the valves and circulation pump (P1) accordingly. In doing so, the control logic prioritizes using air and solar sources whenever feasible, preserving the ground source for peak load periods throughout the season. When the source-side buffer tank is thermally charged or HP is in

standby mode, non-standard operations can be carried out, such as thermal regeneration of the ground source using air or solar energy. The implementation of the heuristics like those, calculation and comparison of existing renewable sources of thermal power, in real-time, allows for making the hierarchy among different states, choosing the one with the optimal “cost-effectiveness”. Furthermore, super users are allowed to fine-tune this rule-based algorithm, by adjusting the hyper-parameters and tracking the outputs of the algorithm through the dedicated HMI screens.

Temperature regulation strategy

Concerning the requirements for air conditioning and the operation of the user side of the plant, Figure 2, the heat pump (HP), once operational, keeps the user-side storage tank (BF2) thermally charged and at the temperature set by the user. It also provides thermal energy to the interior space indirectly by turning on the RF, turning on the AHU, or turning on both the RF and the AHU at the same time.

In configuration when only RF is active, the PLC takes charge of controlling the single-speed pump within the radiant floor controller group. This control is based on a hysteresis curve, and its threshold can be adjusted by a super user. The desired temperature for the RF supply water is determined by the output of the indoor air humidity controller, which is particularly important during the summer season. When only the activation of the AHU is requested, the indoor temperature is regulated using a PID control with hysteresis, which controls the speed of circulation pump P2. To account for the fact that users may not easily detect small temperature changes around the set point, a user-defined dead band is employed to prevent frequent changes in the actuator's state. When both terminal units are engaged in air conditioning, the temperature regulation becomes more complex, following a control theory concept known as a multivariate load-sharing structure. In this structure, multiple available actuators operate sequentially, passing control to one another in a predetermined order until thermal comfort is achieved, all while minimizing electrical costs. Two versions of this structure have been developed

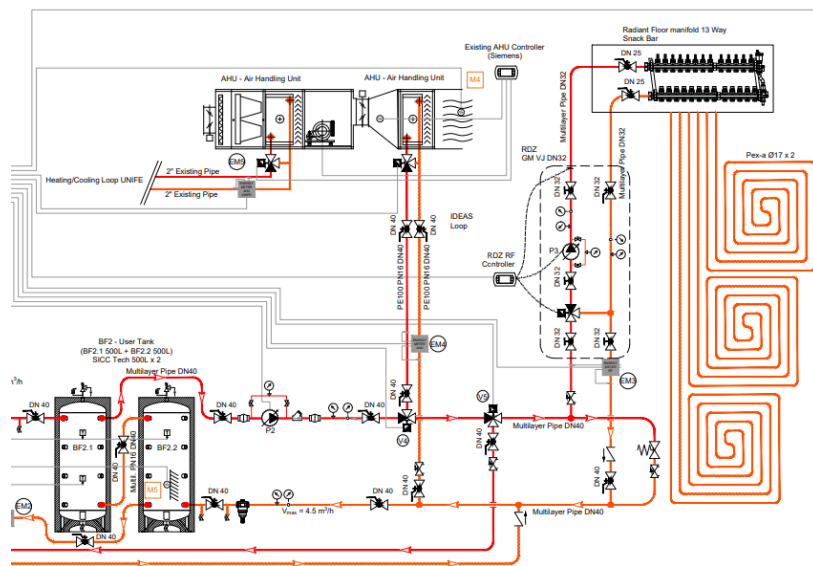


Figure 2 - User side of the installation (excerpt from P&ID)

(refer to Figure 3) and are available for selection. In addition to regulating indoor air temperature, the supply air temperature of the AHU is also controlled. A cascade control system is implemented, with the regulation of these two temperatures interlinked, as shown in Figure 4. During normal plant operation, the old heat exchanger (HX) of the air handling unit (AHU) remains inactive. This status is communicated through a voltage signal sent to the KNX controller, Table 1, which is responsible for controlling the opening of the mixing valve at the HX's inlet port. Prior to the installation of the new system, this HX served as the sole terminal unit and can still operate independently when the new HVAC system is turned off or when it is unable to provide thermal comfort within the facility.

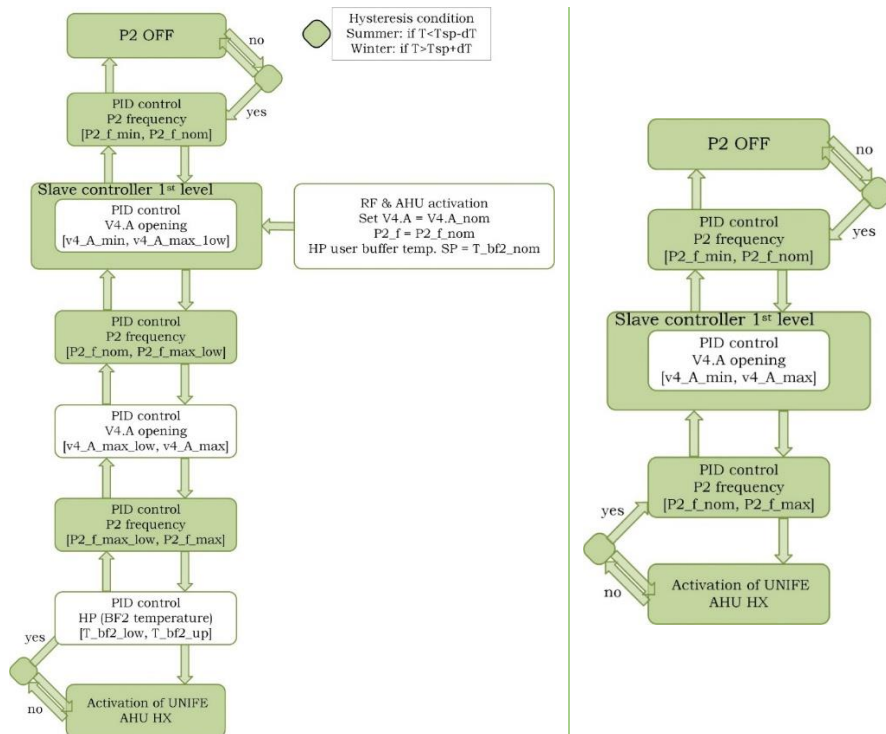


Figure 3 – Multivariate load-sharing structure – version from October 2022 (left) and version from April 2023 (right)

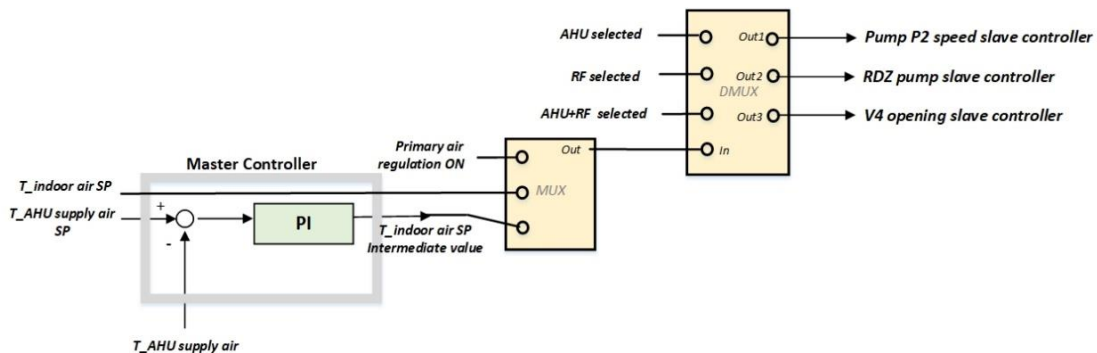


Figure 4 – Indoor air temperature – AHU supply air temperature cascade control

HMI functionalities

The design of the HMI screens was an iterative process, that involved both developers and end-users in the decision making. Basically, it has been made as a trade-off of several functional and user requirements. Firstly, its utilization by the University of Ferrara research community, conducting research on the installed technologies, imposed realization in English. The second, experimental purpose of the plant, demanded deeper level of user interaction with the plant and control system to fine-tune the algorithm even in the absence of developers and therefore, development of additional HMI features has been required. The third, standard, optimized interface has been developed too, to ensure efficient and user-friendly interaction between the user and the SCADA system. Overall, depending on the level of authority, three different user configurations have been realized: *super*, *technician* and *final*, with different degrees of freedom in controlling the system, Figure 5.

Custom-made to meet the needs of this specific plant, HMI still does its main purpose – enables users to monitor the considered process, command actions interactively, manually enter data, safely stop devices or the entire plant. All current views are obtained from a real-time database (RTDB), and dynamic details are continuously updated and displayed using vector graphics. This real-time display empowers operators to make timely decisions and take appropriate actions. Finally, all the visible, HMI components have been drawn from the scratch, relying on the IMP VIEW4 tools for editing and HMI configuration. To illustrate its capabilities, an overview of the most important HMI functionalities has been provided, especially focusing on the Main screen, Figure 6.



Figure 5 - HMI Login form

As the name indicates, it provides all the relevant information any of the users would seek, at first glance, Figure 7: an indicator displaying the general operating regime (“Control status”, which can be Automatic, Semi-automatic, or Manual), an indication of the active layout on the source system side (or the active “System status”, which can be one of the following categories - G, A, S, GA, GS, GA UTS, GS UTS, PVT AS, IDLE), and active operating regime in terms of “Season” (Winter or Summer).

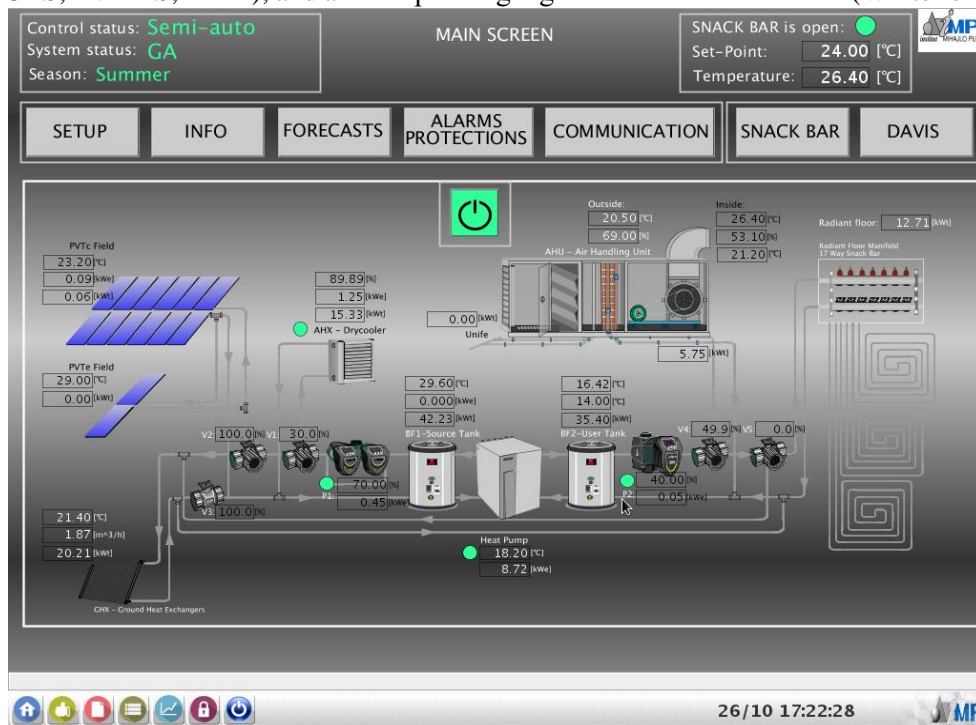


Figure 6 – Main screen appearance, displaying real-time information.

Several important components are shown in the upper right corner of the screen. It denotes whether the snack bar is now open, which determines whether air conditioning is needed. It also presents the current

measurement of the indoor air temperature and there is an active field, where the current temperature set-point value is displayed, and the user can modify this value by clicking on it.

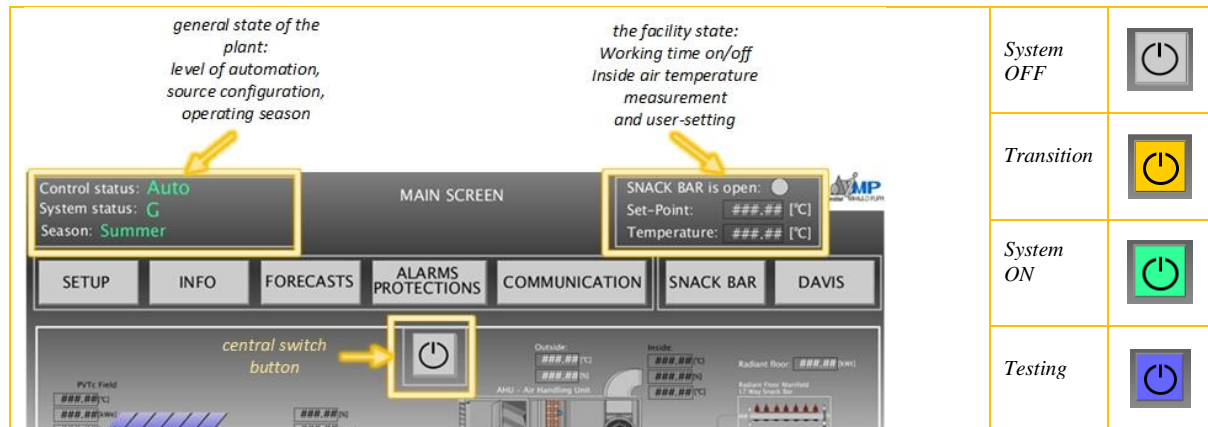


Figure 7–Main screen: General information frames and Central Switch

The central part of the main screen represents the simplified layout of the demo plant piping.

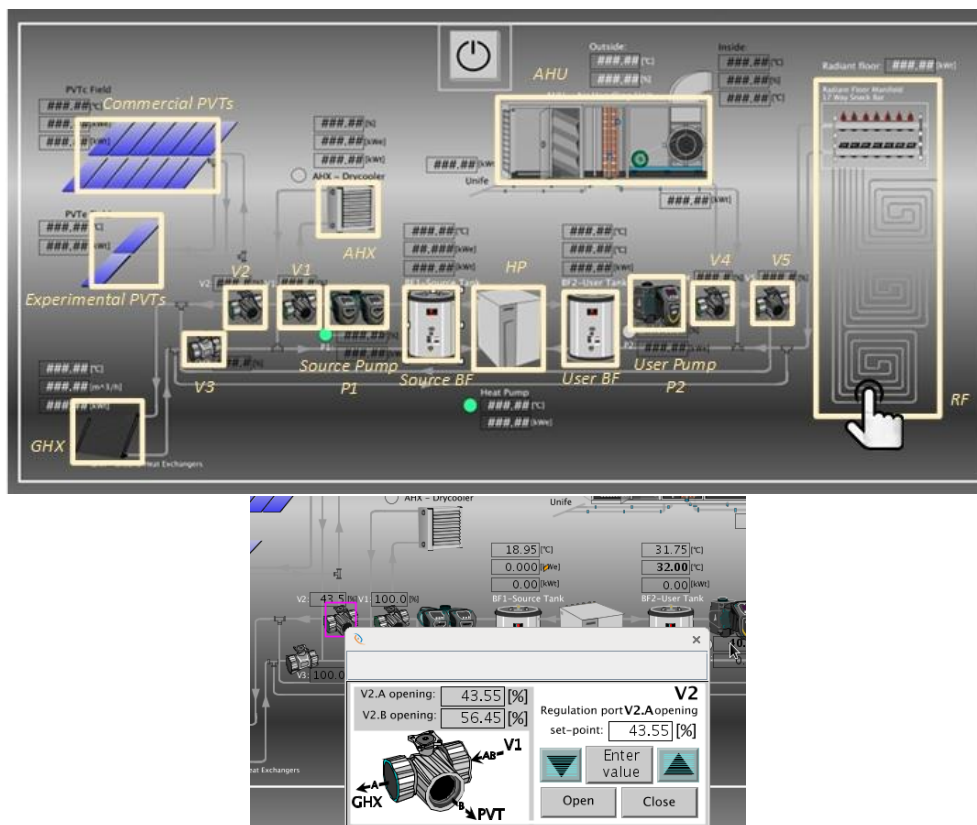


Figure 8 – Main screen: Interactive components for command-windows opening.

By clicking on each component, marked areas in Figure 8, the pop-up window will appear, and the user can get more detailed information regarding concrete device. Given the example, clicking the depicted active area or field will result in the appearance of the valve V2 settings window, where besides information about valve opening and its current set-point, there are commands for its custom partial or complete opening and closing.

Below the central switch button, there is a navigation menu, Figure 7, with set of buttons that can open different screens of the HMI. Main settings related to the control application operating regime, can be made through the widgets of the Setup screen, Figure 9. The screen's appearance reflects the differentiation in control rights among different users. The final user, in the truest sense, interacts with the system by selecting a season choice – Auto/Summer/Winter (or Cooling/Heating) and by adjusting the air temperature inside the space. The technical user is granted a medium level of controlling permissions. The technical user can choose the source-side control mode and the automation level of control (Auto, Semi-auto, Manual), in addition to the control features available to the end user. The highest level of authority belongs to the super user, and normal HVAC application users are not granted this kind of management over the system. Basically, available functionalities are:

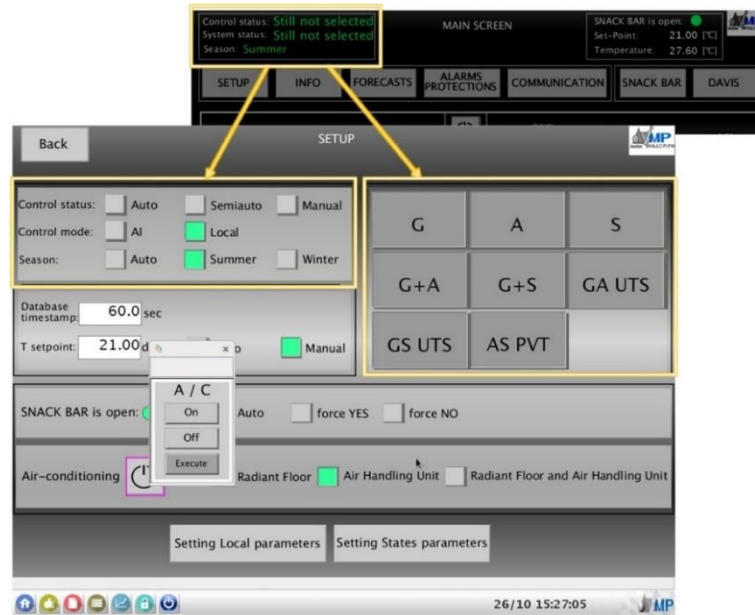


Figure 9 – Setup screen

- Control status selection,
- Control mode selection,
- Season selection,
- Archiving database timestamp selection,
- Indoor temperature set-point adjustment,
- AHU supply air temperature set-point adjustment,
- the facility working time forcing (A/C, disabled during non-working hours of the snack bar),
- Air-conditioning turning on/off,
- Selection of terminal units to be engaged in A/C,
 - Radiant floor,
 - Air-handling unit,
 - Both radiant floor and air-handling unit active in indoor space temperature regulation,
- Version of the PLC regulation temperature software,
 - When both RF and AHU active in A/C, different possible algorithms can be run, for which multivariate load-sharing structures differ.

Finally, this screen provides further access to nested screens with advanced experimentation supported, and their (and the remaining screens') functionalities explanation exceeds the scope of this technical elaboration.

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ПРИЛОЗИ

- Доказ: Протокол о тестирању од стране корисника
- Листа раније прихваћених техничких решења (појединачно по аутору и за све ауторе)

Протокол о тестирању од стране корисника:

Herein, we confirm that the technical solution entitled:

**Control Application for A Multi-Source Heat Pump-Based Heating
Ventilation and Air-Conditioning System**

developed by the Institute Mihajlo Pupin, Belgrade, Serbia, has been successfully tested by partners from the University of Ferrara, Ferrara, Italy.

The solution relies on the Institute's proprietary VIEW4 SCADA system h/w and s/w technology, custom-designed to be coupled with existing technologies within the equipment of the pilot site plant, located in the University of Ferrara, Italy. It provides complete automation and control of the heating, ventilation, and air-conditioning system, representing an instance of a multi-source heat pump system. The solution has been tested and commissioned through joint activities of Institute Mihajlo Pupin and the University of Ferrara, in the framework of the Horizon 2020 IDEAS project.

This confirmation has been issued on the request received by the Institute Mihajlo Pupin and in relation to the monitoring of the innovation activities by the Ministry of Education, Science, and Technological Development of the Republic of Serbia.

Ferrara, Italy,
2024-01-22

Prof. Michele Bottarelli,
Associate professor at University of Ferrara,
Department of Architecture



Катарина Станковић, листа техничких решења

M85

1. Деа Пујић, Валентина Јанев, Марко Јелић, Катарина Станковић: “Естиматор производње електричне енергије ветрогенератора заснован на машинском учењу”, 2022, ТР32010

Марко Батић, листа техничких решења

М81

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2. Марко Батић, Дејан Пауновић, Сања Вранеш: "Систем за симулацију и планирање дистрибуиране микро-мреже базиране на обновљивим изворима енергије", 2013, ТР32010

М82

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