Controller-in-the-loop - New ways of optimizing costs and quality of heat pump systems

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The complexity of heat pumps systems is constantly increasing, and refrigerants are evolving to comply with the F-Gas regulation of the European Union. As a result, the requirements of the heat pump system controllers are also growing. Thus, precise testing of such complex controllers will become more important. Controller tests are usually done regarding the software, or after the production of prototypes. Software tests can only partially map the real operation, whereas prototypes can cover it completely, but are very expensive and required changes to prototypes are very costly. To test the controllers without expensive prototypes, but with conditions very similar to real operation, the controller-in-the-loop (CIL) is suggested. This approach is explained in some detail and illustrated with a real example.

Introduction

The development in the heat pump technologies sector leads to increasingly complex systems. In addition to the complexity of the design, older refrigerants are phased out to comply with the F-Gas regulation [1] and new refrigerants are entering the market. Thus, the requirements for the control of such systems are also gradually becoming more demanding, and more components must be correctly controlled in different configurations and different operating states. This growing complexity also increases the probability of mistakes being made during the development of control concepts. Although the software of controllers are already being tested, real operation cannot yet be accurately represented by this type of tests. For example, the communication level, which is usually done via MODBUS [2] or BACnet [3], and the time delays that occur both through communication and through the hardware installed in the real controller, are missing. It is also difficult to map disturbances caused by data collisions or losses. This leaves only the expensive development of prototypes for classic controller tests. In addition to the high costs, prototypes are difficult to adapt after construction. Therefore, already in the concept development phase, significant effort has to be made to develop a stable and efficiently controlled heat pump system. In order to avoid faulty prototypes, the development of new and innovative systems must be slowed down in favour of more stable systems based on conventional approaches.

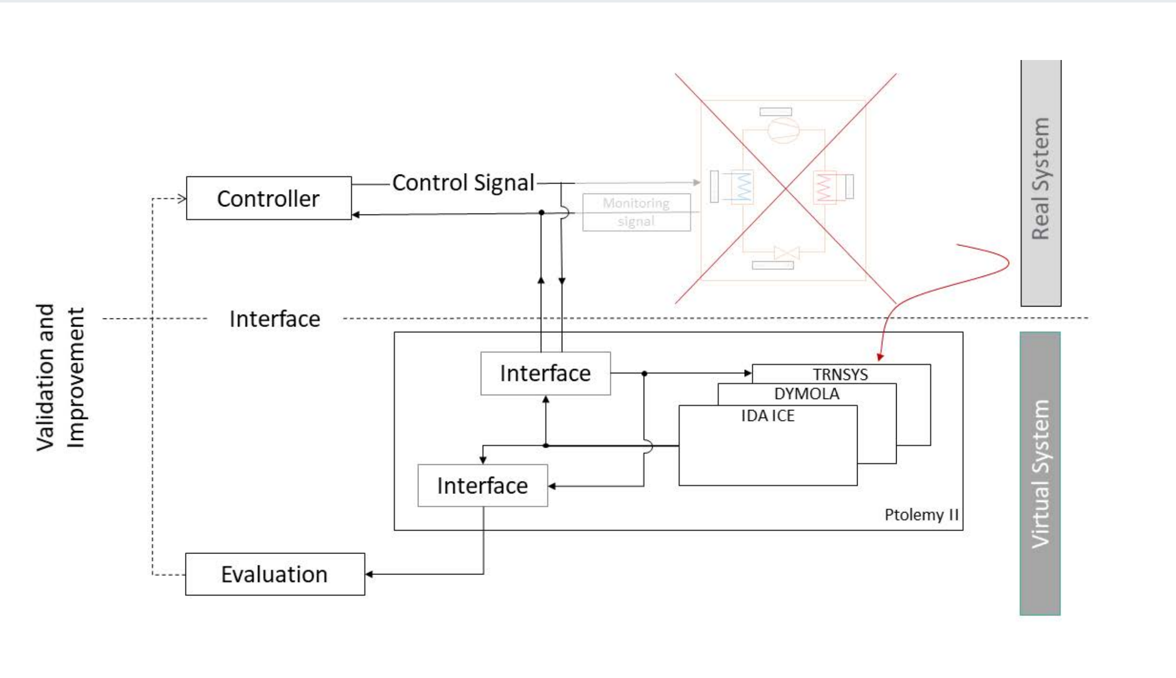

Fig. 1: Concept of Controller-in-the-Loop

In this article, the terms heat pump system and refrigeration system are used interchangeably.

One possible solution to these problems is the concept of Controller-in-the-Loop (CIL). This concept is based on the hardware-in-the-loop (HIL) [4] approach, except that in this case the controller is the physical element and the system to be controlled is the virtual one. This concept is used e.g. for test benches to connect the digital and real world with each other and to make use of their respective advantages. This allows virtual physical models of e.g. drive motors to be tested or further developed with real control electronics without having to build expensive prototypes or test benches. The same concept can also be used for the heat pump sector. Here, a virtual (part)-model of the refrigeration circuit is mapped in a suitable simulation tool and coupled with a real controller intended for this purpose. Furthermore, the controller behaviour can be checked for correct function before the actual initial operation. With the simulation of different test scenarios, e.g. varying source and sink capacities or components with other characteristics, investigations can be made about the behaviour of the refrigeration system and the associated control behaviour.

Concept description

Within the CIL approach, the real environment is converted into a virtual environment, which is connected with a physical controller, see Figure 1. Hence, two different levels must be considered: the communication level and the simulation level. At the communication level, which is represented in Figure 1 as Interface, a connection between controller and computer must be established, where the data can be transmitted using protocols or direct connections. Hereby, different protocols are available for communication, for example Modbus RTU and TCP/IP as well as BACnet. Depending on the protocol used, the controller must be connected in different ways, for example Modbus RTU with a serial, Modbus TCP/IP and BACnet with a RJ-45 connection. After setting up a connection successfully, the respective protocol must be correctly parameterized on both sides, the master (PC) and the slave (controller). If the connection is analogue and the signals are transmitted directly without using a protocol, Data Acquisition Systems (DAQ) must be used, which convert the analogue signals into digital ones that can be decoded by the PC.

On the simulation level, different tools are available, which are appropriate for various systems. For example Energy Plus, IDA ICE and TRNSYS are well suited for building simulations and Dymola/Modelica [5] as well as MATLAB/Simulink for simulations on the component level. Once the real system has been modelled virtually, it must be connected to the controller. Therefore a simulation environment must be used, whereby Simulink and the open source tool Ptolemy II are appropriate solutions for this purpose.

Coupling of physical controller and numerical refrigeration circuit model

The CIL approach described above is demonstrated in the following by coupling a real Carel cPCO controller with a virtual refrigeration system. In this example all communication is done via Modbus RTU and a RS-485 to USB converter. For the simulation of a refrigeration circuit Dymola/Modelica was chosen as a suitable simulation environment. With this tool, the real system can be represented sufficiently accurately to simulate the system dynamics. Ptolemy II was used for the present example for coupling the virtual and the real world because of its simple extensibility, since own functions can be programmed and integrated in Java. In this way a Modbus RTU Reader and Writer were implemented.

Figure 2 shows the process starting from an enclosed heat pump model developed in Dymola/Modelica ending up in an interconnected model to the real environment and integrated into Ptolemy II. The heat pump is based on components from TLK Thermo's TIL library, where components of a compressor, condenser, expansion valve and evaporator for space heating and hot water are interconnected. This model represents the use case of building retrofitting with a brine-water heat pump. Table 1 shows the model parameters. A piston compressor with On / Off control at 50 Hz mains frequency is used. The operating limits are selected according to the application for domestic hot water and space heating, which means a maximum sink temperature of 60 °C and a minimum source temperature of -15 °C. The suction gas super heating temperature is set to 7 K. The circulation pumps on the source and sink side are on/off controlled. It should be noted that the numerical model does not have any control architecture implemented. The control mechanism is provided from the hardware controller.

After successful modelling, the virtual sensors and actuators, which are needed for the subsequent control, are defined as inputs and outputs of the model. Afterwards it is possible to create a Functional Mockup Unit (FMU) to add it to Ptolemy II. As a last step, the inputs and outputs of the DYMOLA FMU must be connected to the Modbus RTU communication blocks and communication with the physical controller is possible.

The controller will be tested in consideration of the above mentioned boundary conditions in terms of security

Table 1: Model parameters.

Refrigerant	Compressor	Heating capacity	Max. sink temperature	Min. source temperature	Suction gas superheating	Sink pump	Source pump
R1234zee (Low GWP)	Piston On/off	7kW @B0W35	60°C	-15°C	7K	On/off	On/off

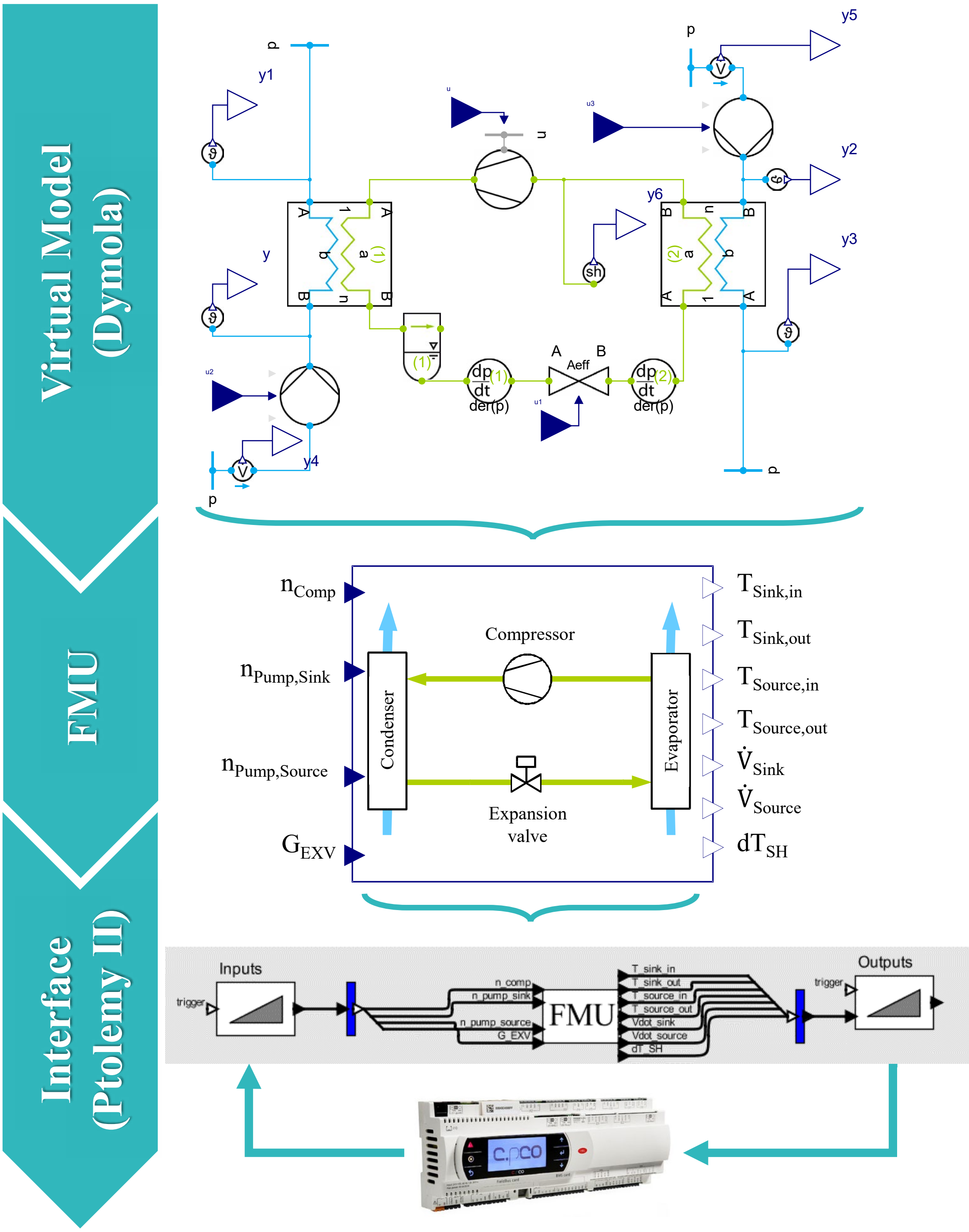

Fig. 2: Processing an enclosed Dymola/Modelica model into an interconnected model to the real environment and integrated into Ptolemy II.

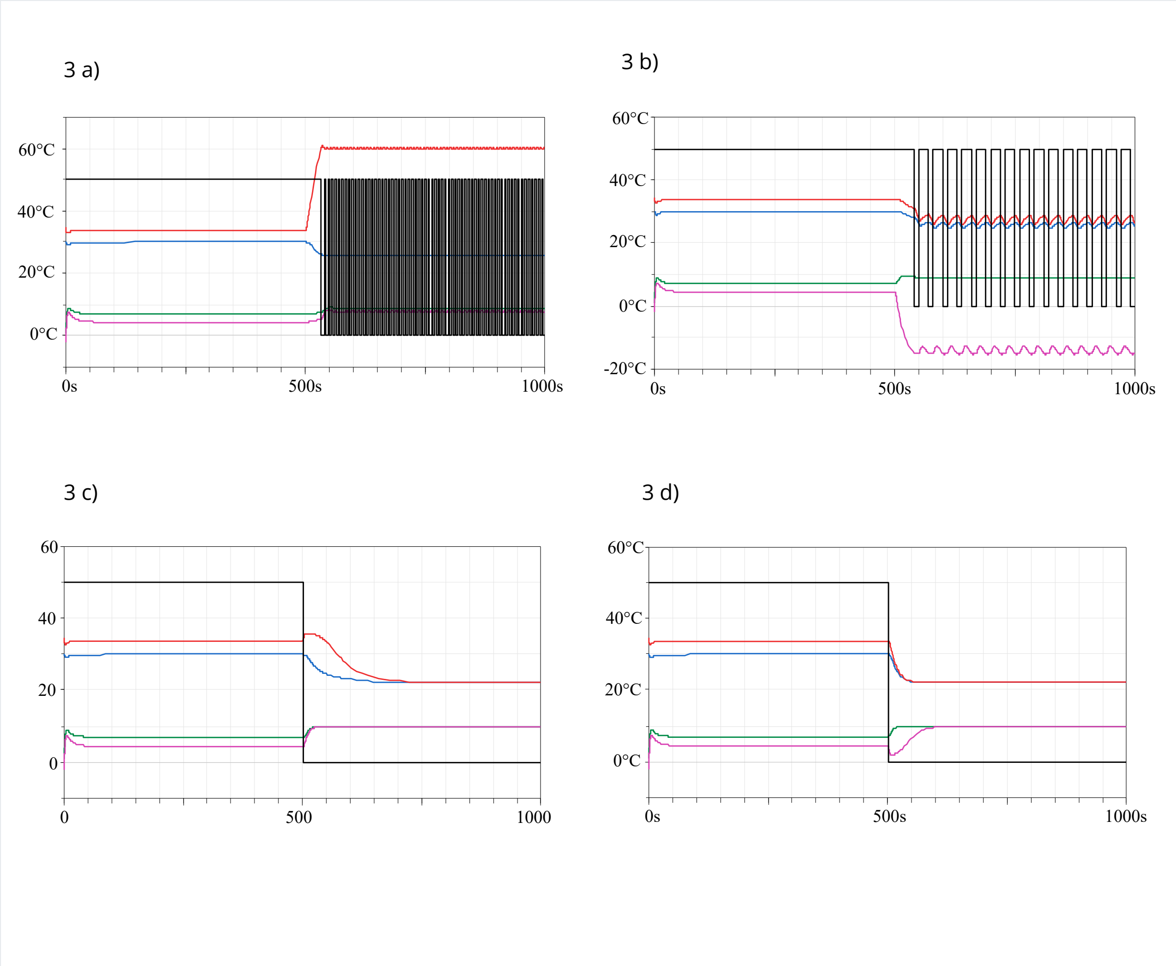

Fig. 3: Induced abrupt mass flow drop on sink/source side at 500 s
3a) Sink side, incorrect controller parameters. 3b) Source side, incorrect controller parameters.
3c) Sink side, corrected controller parameters. 3d) Source side, corrected controller parameters.

management. Following the heat pump test standards EN14511 [6] and EN14825 [7], the sink flow and the source flow are abruptly set to about 0 m³/h. If the controller parameters are set correctly, the minimum flow rate protection should switch off the compressor immediately preventing any damage to the system.

Results

As an example of error detection, figures 3a-3d show the effects of abruptly reduced water-side volume flows on the sink (figs 3a, 3c) and source (figs 3b, 3d) side at 500 s, if the minimum volume flow rate protection was implemented incorrectly. Figs 3a and 3b show the effects of non-identification of the error.

On the sink side (fig 3a), the sink outlet temperature (red line) increases due to the strongly reduced water-side flow rate. A further protective mechanism intervenes and shuts down the compressor (black line) when the maximum allowed sink side temperature of 60 °C is reached. Once this temperature has dropped below the maximum sink temperature, the compressor is switched on again. This cycled operation leads to a significant number of compressor starts in a short amount of time, which reduces the compressor lifetime. After identifying the error, the minimum flow rate has been adjusted and the controller shuts down the refrigeration circuit after error identification, (fig 3c).

A similar behaviour can be observed on the source side (figs 3b, 3d). Here, a minimum return temperature (pink line) must not drop below the minimum flow temperature (e.g. -15 °C frost protection in the piping), which again leads to an increased number of compressor starts (fig 3b). Here, the error is also corrected by adjusting the switch-off volume flow and the refrigeration circuit is shut down correctly (fig 3d).

Conclusions

In this article, the CIL approach was explained in some detail and completed with a practical example. Due to the good availability of different protocols, which are already handled by every established controller manufacturer, coupling with a PC is quite uncomplicated. Even analogue signals can be converted into digital signals with DAQ devices and made available on a PC. On the PC side, different well-established simulation programs are available to represent different systems virtually. These programs can be coupled to the real environment with different tools, if the protocols used are correctly implemented. By successfully coupling a real controller with a virtual plant model, errors could be identified and corrected without prototypes and without the risk of damaging the plant. In contrast to a purely software-based control strategy test, it was possible to test with a dynamic model and under consideration of all influences, e.g. communication delays. After such tests, the controllers can be connected directly to the real device without considering possible porting errors of the control software from the PC to the controller.

Acknowledgements

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References

[1] European Parliament, REGULATION (EU) No 517/2014 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006. p. 36.

[2] "The Modbus Organization." https://www.modbus.org/ (accessed Oct. 07, 2020).

[3] "BACnet Website." http://www.bacnet.org/ (accessed Oct. 07, 2020).

[4] O. M. Abdalla, S. A. Hammad, and H. A. Yousef, "A Framework for Real Time Hardware in the loop Simulation for Control Design," ArXiv14101342 Cs, Oct. 2014, Accessed: Oct. 07, 2020. [Online]. Available: http://arxiv.org/abs/1410.1342.

[5] "Dymola - Dassault Systèmes®." https://www.3ds.com/products-services/catia/products/dymola/ (accessed Oct. 07, 2020).

[6] DIN, "DIN EN 14511-3:2019-07." Jul. 2019, [Online]. Available: https://www.beuth.de/de/norm/din-en-14511-3/298537847.

[7] DIN, "DIN EN 14825:2019-07." Jul. 2019, [Online]. Available: https://www.beuth.de/de/norm/din-en-14825/286479610.

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