13th IEA Heat Pump Conference
May 11-14, 2020 Jeju, Korea

Possibilities and constraints of grid flexible control of todays and tomorrows heat pumps

Markus Lindahl[a], Tommy Walfridson[a], Jessica Benson[a], Oskar Räftegård[a], Ola Gustafsson[a], Caroline Haglund Stignor[a]

[a]Energy and Circular economy, RISE Reseach Institutes of Sweden, Box 857, SE-501 15 BORÅS, Sweden

Abstract

In this article possibilities and constraints of grid flexible control of heat pumps for domestic heating are investigated. By creating dynamic coalitions of heat pumps and control their power consumption, demand response can be offered to the power grid. For a functional power grid, the heat pumps electrical power consumption needs to follow the electrical grids needs accurately.

Possibilities to externally control the power consumption of a ground source heat pump has been investigated. Both direct control, where the compressor speed is set directly, and indirect control, achieved with outdoor temperature sensor override, has been evaluated. For the evaluation a test cycle for laboratory testing of a heat pumps grid flexibility has been developed.

Based on the test cycle, the heat pumps possibilities to follow the load profile using both direct and indirect control was tested in laboratory. Both control methods were possible to use, with the direct control being significantly more accurate. Using direct control, the power consumption of the compressor managed to be within ±10% of the stated power consumption for 97% of the time.

Keywords: Grid flexible heat pump; Heat Pump control; Smart grid; Demand response; Heat Pump

1. Introduction

The European power system undergoes a major transformation driven by a steadily increasing share of power from renewable intermittent energy sources, such as wind power and solar energy. When the production of electric power from intermittent sources increases, the need to control the variations in the power system increases as well [1][2]. Heat pumps, with their possibility to convert power to heat, can support the transformation of the power system. Making use of the building's thermal inertia in combination with controlling the heat pump´s power consumption makes it possible to use the heat pump to provide demand response [1]. Historically heat pump design has focused on providing a good indoor climate and domestic hot water (DHW) with as high efficiency as possible. In the future with more and more variable power production it will likely be of greater importance to provide comfort with low impact on global warming rather than with as high efficiency as possibility.

By external control of the heat pumps and their power consumption, demand response can be offered to the power grid. The term "demand response" includes controlling the power consumption to better match the consumption with the power supply. Demand response can be used to avoid power peaks, balance the power consumption, avoiding curtailment of power production from intermittent renewable sources etc. One way to offer a larger flexibility in electric power is to make dynamic clusters of heat pumps, giving higher flexibility when controlled together [1][3].

1.1. Scope

The objective with the article is to evaluate different strategies for indirect and direct control of a grid flexible heat pump and give recommendation of the best way to externally control a heat pump with variable speed compressor for offering grid flexibility. A grid flexible heat pump is defined as a heat pump that can adjust its electrical power use to external demands.

1.2. Method

Two different strategies for heat pump control have been evaluated by laboratory tests of a ground source heat pump with a variable speed compressor. The strategies evaluated are indirect control via temperature sensor override and direct control of the heat pumps compressor speed. In addition, other possibilities and constrains of heat pump control have been evaluated using a literature survey and a questionnaire sent out to four Swedish heat pump manufacturers.

1.3. Delimitations

The article focuses on how to control the heat pumps power consumption externally. How the power profile for offering demand response is calculated and distributed to the individual heat pumps are out of the scope of the article and only briefly described. The article studies the control of the heat pumps power consumption and heat production related to space heating, production of domestic hot water is not included.

1.4. Background

The benefit with heat pumps, when it comes to demand response, is their possibility to transform power to heat. In combination with the thermal inertia in buildings, or thermal storages, it gives a possibility to control, within certain limits, when the building needs to be heated and still keep a good indoor climate. By controlling the power consumption of the heat pump, it is possible to help balancing the power systems variations in supply and demand. But controlling the power output from a single heat pump gives low flexibility to the grid, in order to provide a useful size of power to use for demand response a coalition of heat pumps needs to be controlled together. In the EU project Flexible Heat and Power (FHP) [4], which work the article is based on, this is done in several steps. First the available thermal flexibility from the individual buildings is calculated, followed by aggregating the flexibility from all individual buildings for a neighborhood or a community. Then the aggregated plan can be used to offer balancing services to the local distribution system operator (DSO) or the balance responsible party (BRP). Finally, the decided control of the heat pump coalition will be disaggregated and dispatched to the individual heat pumps, where each heat pump is given a power profile to follow. This article focuses on the last step, how to control the heat pumps power consumption and follow a decided power profile given by an external party.

1.4.1. Heat pump control

There have been other projects during the last years investigating the use of heat pumps to offer demand response in different ways. How the heat pumps power consumption is controlled varies. In some projects an off-signal is sent to the heat pump. One example is the EU project EcoGrid [5], the project demonstrated the operation of a power system with high amount of renewable and variable energy resources on the Danish island of Bornholm. The operating tools for heat pumps developed in the project had the possibility to send an off signal to the heat pump for a certain time period.

Another way to control the heat pump is based on the German “Smart grid ready” or “SG ready” standard. It is a standard for smart control defined by the German Bundesverband Wärmepumpe e.V. [6]. The standard makes it possible to send a signal to the heat pump that activates one of the four defined modes. The activation of each mode is done based on how two terminals are open (0) or closed (1). The setting of the terminals activates different setting of the heat pump control. When one of the modes is activated, the heat pump is programmed to respond in a certain way. The exact response for each mode is not defined by the standard and can vary from one heat pump model to another.

The four defined heat pump working modes are [7]:

1. Blocking mode: HP is switched off, until storage reaches its lower allowed temperature level. (1:0)
2. Normal mode: HP operates with normal set-points. (0:0)
3. Low price mode: HP is switched on. (0:1)
4. Over capacity mode: HP is switched on, storage temperatures increased to the maximum temperature allowed by the HP. (1:1)

2. Strategies for heat pump control

One important step in the chain to provide demand response is to be able to control the heat pump based on external signals in order to make the heat pump consume the amount of electricity asked for. Both sending an off signal to the heat pump or using the SG ready standard gives a very rough control of the heat pumps power consumption. In order to make the heat pump follow a defined power profile a method with higher accuracy is needed. Two alternative methods are evaluated in order to find a way with higher accuracy. External control of a heat pump can be divided into two main categories, direct- and indirect control.

2.1. Indirect control

The heating demand of a building is dependent on the outdoor temperature and a heat pump is programmed to adjust its heat production based on the outdoor temperature. Most heat pumps are equipped with an outdoor temperature sensor, giving information about actual temperate, used to estimate the heating demand of the building. At low winter temperatures the auxiliary heater may need to start to cover the total heating demand of the building. Manipulating the temperature sensor and sending a fake outdoor temperature to the heat pump is a possible way to indirect control the heat pumps heat production and power demand. An alternative way to control the heat pump indirect is to adjust the heat pumps heating curve. In the tests related to this project the outdoor temperature sensor was replaced with an adjustable precision potentiometer making it possible to manually set the outdoor temperature wanted.

2.2. Direct control

At direct control the heat pumps ordinary, internal control to set the compressor speed and switch between space heating and production of DHW is bypassed and the compressor is controlled directly. This makes it possible to control the heat pumps power consumption fast and with higher accuracy. To make this work it is necessary that the heat pumps is prepared for external control and that it is possible to communicate with it. No heat pump on the market has this functionality today.

During the laboratory tests with direct control a software developed by the heat pump manufacturer of the tested heat pump was used. The software is normally used for internal testing by the manufacturer. Via a computer connected to the heat pump, the software made it possible to set the compressor frequency directly. As a complement to the software an add-on was created. The add-on makes it possible to set the frequency profile asked for via a csv-file. This made it possible to create a test sequence that automatically changes the compressor speed at desired times, making it easier to test longer sequences with changing compressor speed or to make fast changes.

2.3. Constrains in compressor speed change

The heat pumps on the market today are developed to give high comfort with as high efficiency as possible. But in order to be flexible, the heat pump needs to handle fast changes in compressor speed. A survey sent out to four Swedish heat pump manufacturers showed that different manufacturers have different approaches, comparing the time inverter heat pumps took from off mode to maximal heat production or from the lowest compressor speed to the highest. Figure 1 shows large differences in time going from minimum to maximum speed depending on the choice of heat pump model. Note that for the laboratory test presented in this article “HP A” has been used.

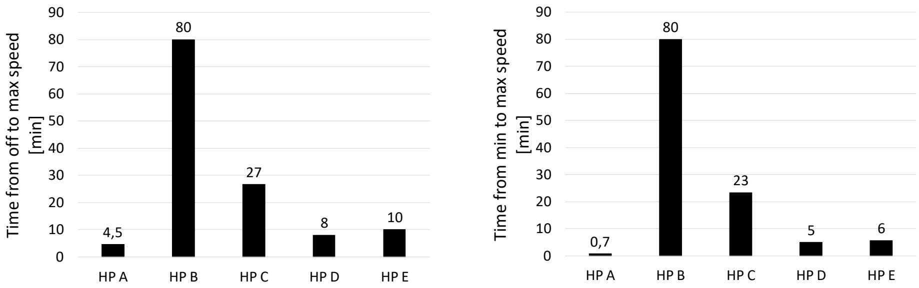


Figure 1. Time from compressor off to full speed (left) and from running at lowest compressor speed to highest compressor speed (right).

Another constraint is the start-up phase, where the compressor typically needs to run at a fixed, midrange speed for minutes, to secure lubrication before the speed asked for can be set. The speed control also varies between different manufacturers, not all use stepless speed control, but instead use fixed speed in steps to alter between. The reason is to have better control of the performance, as stepwise means most operation modes can be tested and optimised, and since the heating system and building has high inertia, there is little point of controlling speed exactly.

3. Test method

The performance using both indirect and direct control of a ground source heat pump was tested in laboratory based on a standardized test cycle for evaluating the possibilities to control a grid flexible heat pump. In addition, a number of 24h test profiles were developed and tested using direct control.

3.1. Test cycle

In order to standardise testing and evaluation of the control of a grid flexible heat pump an eight-hour long test cycle for laboratory testing was developed. The purpose with the test cycle is partly to evaluate how close the heat pump in combination with the external control manage to follow the specified test profile. Partly to test if the heat pump control manages a number of functions, such as start and stop of the compressor, changing the compressor speed and start and stop the auxiliary heater, se Figure 2.

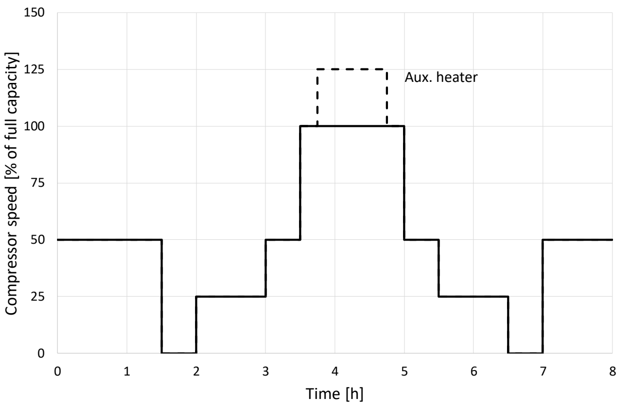


Figure 2. Test cycle for laboratory testing of a grid flexible heat pump

3.2. Key performance indicators

Four key performance indicators (KPI) for the flex function was identified in order to evaluate the results. KPI_1 - KPI_3 expresses how well the heat pump can follow the test cycle, while KPI_4 expresses how the flex function affects the heat pumps coefficient of performance, COP. In Table 1 below each KPI is defined:

Table 1. Definition of key performance indicators for evaluation of grid flexible heat pump control

Key Performance Indicators	
$KPI_{1,\ a\ and\ b}$	Average deviation between the measured compressor speed, heat production or power consumption compared to stated value by the test cycle. The result for KPI_1 is expressed in revolutions per second (rps) or in watt (W). With a: auxiliary heater included and b: auxiliary heater excluded.
$KPI_{2,\ a\ and\ b}$	Percentage of the time the compressor speed, heat production or power consumption is within ±3% of the value given by the test cycle, where the interval, ±3%, is defined at maximum compressor speed. With a: auxiliary heater included and b: auxiliary heater excluded.
$KPI_{3,\ a\ and\ b}$	Percentage of the time the compressor speed, heat production or power consumption is within ±10% of the value given by the test cycle, where the interval, ±10%, is defined at maximum compressor speed. With a: auxiliary heater included and b: auxiliary heater excluded.
$KPI_{4,\ a\ and\ b}$	KPI_4 gives the impact on the heat pump efficiency, COP, related to making the heat pump follow the test cycles variations instead of working on stable conditions. KPI_4 is calculated as the average COP during the whole test cycle (time 0h to 8h) divided by average COP during test time 0.5h to 1.25h (when the compressor is working on stable conditions at 50% of maximum speed). With a: auxiliary heater included and b: auxiliary heater excluded.

4. Results

The results from the laboratory tests with indirect and direct control are presented below, followed by a comparison of the results from the two tests.

4.1. Test cycle, indirect control

During the test a manipulated outdoor temperature was sent to the heat pump making the heat pump change the compressor speed in order to follow the test sequence in Figure 2. This was done manually using a potentiometer. The results from the test is presented in Figure 3 below. The figure shows that the test cycle is followed relatively well, but not perfect. It also shows that the compressor follows the test cycle better than the auxiliary heater does. An additional outcome from the test was that it is easier to follow the profile going up in compressor speed than going down with high accuracy.

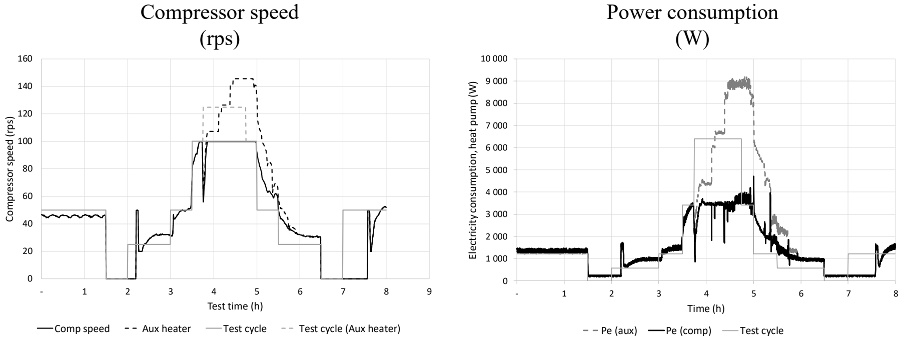


Figure 3. Results indirect control of compressor speed and auxiliary heater via temperature sensor override. Compressor speed (left) and power consumption (right)

The outdoor temperature corresponding to a specific compressor speed and thus a specific heating capacity and electricity consumption is individual for each heat pump, depending on the heat pump model, the heating demand of the building and the heat curve chosen.

4.2. Test cycle, direct control

During the test with direct control, changes to the compressor speed were made manually by a test engineer using the software described in chapter 2.2 and following the test sequence in Figure 2. The results from the test is presented in Figure 4 below. The figure shows that the heat pump compressor follows the test cycle with high accuracy, but it was not possible to activate the auxiliary heater using this version of the program for direct control. The largest deviation of the compressor speed compared to the test cycle occurs after two hours, when the compressor needs to start at 50% before it can reduce the speed to 25% to follow the test cycle. Otherwise the compressor speed follows the test sequence very well.

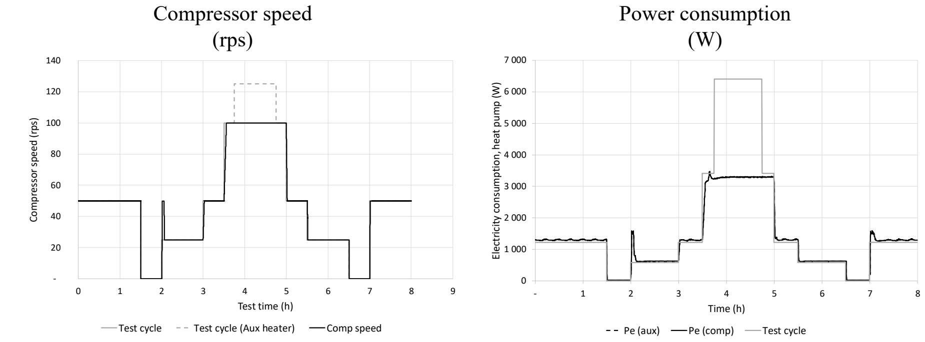


Figure 4. Results for direct control of compressor speed and auxiliary heater. Compressor speed (left) and power consumption (right)

4.3. Comparison results indirect and direct control

Comparing the results from the two laboratory tests shows that the direct control follows the test cycle much better. Looking at the compressor only, the direct control is in average 1rps from the set value compared to 9rps for indirect control. For the total, also including the auxiliary heater, the direct control is approximately 10rps better, even though the direct control function couldn't start the auxiliary heater.

Table 2. Summary of test results, results for $KPI_{1\text{-}3}$ based on compressor speed.

	Total (Auxiliary heater included)		**Compressor only** (Auxiliary heater excluded)	
	Indirect control	Direct control	Indirect control	Direct control
KPI_1 Average deviation from test cycle	14rps	4rps	9rps	1rps
KPI_2 Time share within ±3% of the test cycle	24%	85%	36%	97%
KPI_3 Time share within ±10% of the test cycle	62%	85%	75%	98%
KPI_4 Decrease COP			-13%	-11%

Looking at KPI_2, the time within ±3% of the set value, there is a large difference between direct and indirect control, but looking at KPI_3, the time within ±10% of the set value, the differences has decreased. This indicates that the indirect control can follow the cycle roughly, but if high accuracy is needed direct control is much better. KPI_4 shows how COP is affected by using the heat pump for flexibility services following the test cycle in Figure 2. In this test COP decreased with approximately 10-15% following the flexible test cycle instead of running the heat pump at stable condition with a compressor speed at 50rps. Additional tests show that the impact on COP depends on the shape of the power profile asked for, see chapter 4.4. Since neither the direct control nor the indirect control managed to start the auxiliary heater correctly, the results on how COP is affected for the total is not included in the results but starting the auxiliary heater will make COP decrease further.

Table 3. Summary of test results, results for KPI_{1-3} based on power consumption.

	Total (Auxiliary heater included)		Compressor only (Auxiliary heater excluded)	
	Indirect control	Direct control	Indirect control	Direct control
KPI_1 Average deviation from test cycle	900W	470W	370W	100W
KPI_2 Time share within ±3% of the test cycle	12%	76%	19%	76%
KPI_3 Time share within ±10% of the test cycle	54%	85%	64%	97%
KPI_4 Decrease COP			-13%	-11%

The heat pump power consumption can be followed within ±100W with direct control, roughly four times better than with indirect control. Comparing $KPI_{2\ \text{and}\ 3}$ in Table 2 and Table 3 shows that with the control methods used in the test it is easier to set the correct compressor speed, translating the compressor speed to power consumption will make the accuracy decrees.

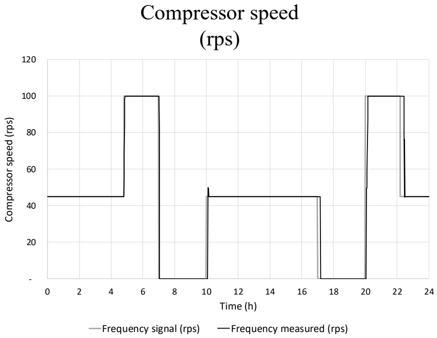
4.4. 24 h test profiles with direct control

In order to further evaluate direct control of the heat pump a number of 24h test profiles were developed and tested in laboratory as a complement to the test cycle. The profiles were based on different scenarios and the purpose with the test was to evaluate how well a heat pump can follow a specified profile using direct control and how the heat pump´s COP, will be affected by following an external profile instead of working in more stable conditions. Below two examples of profiles are presented.

For each test profile a csv-file was created including information about time and compressor speed for every change in speed. Data for the conversion was based on performance tests in the laboratory. The general settings of the heat pump are based on test condition B in table 14 in the test standard for heat pumps, EN14825:2018 [8], representing the conditions at an outdoor temperature of +2°C, for a medium temperature application (typical radiator system) in cold climate.

4.4.1. Profile for peak shaving

A 24h profile for peak shaving has been developed for a theoretic model house with radiator heating. The outdoor temperature is assumed to be +3°C all day, in this case leading to a constant heating demand of 5kW. In the profile the heat pump is assumed to be switched off from 07:00 to 10:00 and from 17:00 to 20:00, it is also assumed that the building has an thermal inertia that makes it possible to switch off the heat pump for three hours and still keep a good indoor climate. To compensate for the period when it is switched off the heat pump produces more heat during other hours. In this case it is assumed that the heat pump will compensate by producing the heat needed at maximum capacity. In the morning this is done before the heat pump is switched of and in the afternoon, it is done after. The result from the test is presented in Figure 5.



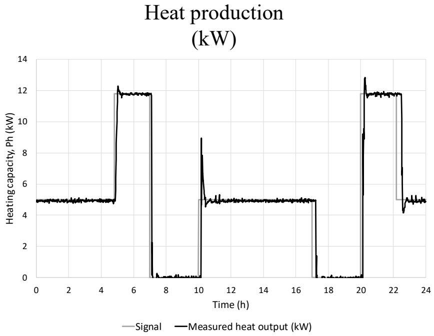


Figure 5. Control signal vs. measured compressor speed (left) and vs. measured heat production (right), profile from peak shaving at +3°C.

The average deviation in heat production between the profile and the measured values from the heat pump test is about 460W. Using a peak shaving profile, as described in Figure 5, instead of working in stable conditions at 5kW heating will decrease COP with 8%, based on data from the laboratory test. Note that the test cannot fully simulate a real installation. In the laboratory tests the return temperature to the heat pump as well as the brine inlet temperature is kept constant independent on how the heat pumps is operated. In a real installation it is a risk that COP will decrease further.

4.4.2. Profile for cost minimization, Aahus Nov 26th

The purpose with the cost minimization profile used for testing is to make a test profile with hourly changes of the heat pumps power consumption in order to minimize the heating cost. For this a simple cost minimization algorithm has been developed for a theoretical model house, based on Excels solver function, with focus on the creation of a relevant test profile. The cost minimization is based on historical climate data in Aarhus, Denmark in combination with historically hourly electricity prices. Nord Pool [9] and DMI [10] are used as a data sources. Aarhus, Denmark November 26th, 2018 was chosen as an example of a day due to its large variations in the hourly electricity prices. This was a day with large changes in electricity prices and a moderate variation in outdoor temperature, from -4°C to +2°C, see Figure 6 below.

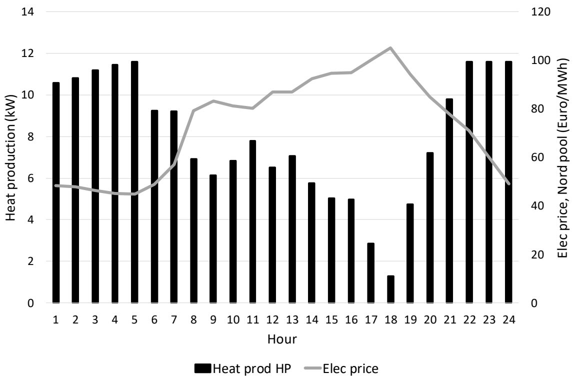


Figure 6. Load profile for heating 26 Nov. 2018 in Aarhus, based on cost minimization in relation to hourly variations in electricity price from Nord Pool [9]

The results from the test is summarized in Figure 7. The average deviation in heat production between the profile and the measured values from the heat pump test is about 380W. Despite a lower COP (-4%) the heating costs decreases with 6%, following the cost minimization profile instead of producing heat based on the actual outdoor temeprature (based on Nord Pool prices, no other costs included).

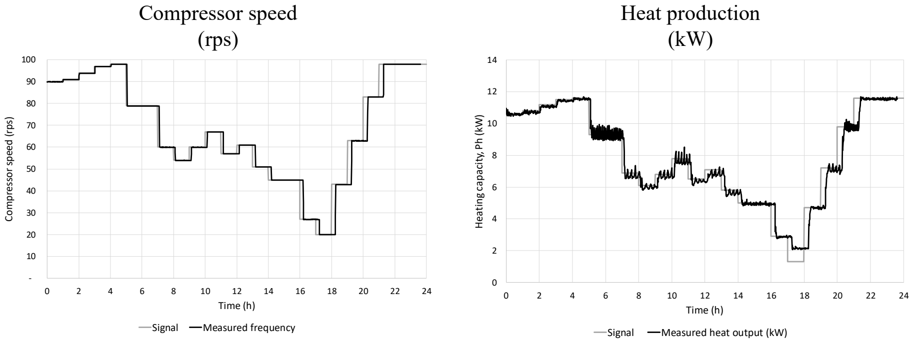


Figure 7. Control signal vs. measured compressor frequency (left) and vs. measured heating capacity (right), profile from cost minimization in Aarhus Nov. 26th, 2018.

5. Discussion

The overall aim with controlling the heat pump performance is to be able to externally control the power consumption and thereby be able to offer demand response. The electricity consumption can be controlled in different ways, which can be divided into two main groups; via indirect or direct control of the heat pump.

The results from laboratory tests with indirect control shows that it is possible to follow changes in a test cycle by using indirect control via temperature sensor override. The heat pump cannot follow the cycle in detail, but the general trend is followed relatively well. A benefit with using outdoor temperature sensor override is that the same software and equipment will work on most heat pump models. The disadvantage is that the equipment must be physically installed at the heat pump and the temperature sensor must be replaced.

A direct control of the heat pump compressor speed or its electricity consumption gives better possibilities to control the heat pump performance with high accuracy. At present day an individual software, overriding manufacturers internal control circuits, will be needed for each heat pump model to use direct control. To make this solution come true, the option needs to be part of manufacturers standardized protocol for controlling the heat pump as a complement to today´s temperature control.

The results from the different 24h-profiles tested in the heat pump laboratory shows that in general the profiles can be followed with high accuracy using direct control. The compressor speed in the profile can be followed with ±1-2rps and the heat pumps total power consumption with approximately ±100W. The evaluation of the results from the laboratory tests show that COP decreases with 0-10% depending on the shape of the profile, if the auxiliary heater is started COP decreases further. In real installations COP might decrease further, since the test rig cannot fully simulate a real heat pump installation. In the laboratory the return temperature to the heat pump is kept at a constant temperature, independent on how the heat pumps is operated. How the return temperature in a building will be affected depending on how the heat pump is controlled is hard to simulate in lab. This can lead to both higher and lower COP. In the same way, as for the return temperature, the brine inlet temperature to the heat pump is kept constant in the laboratory tests. In a real installation the brine inlet temperature will drop if the heat pump works on high compressor speed for a while. This will cause a decrease in COP.

6. Conclusions

Recommendations for external control of the heat pumps electricity consumption can be summarized as:

1. For older heat pumps or non-premium heat pumps sold today:
   Outdoor temperature sensor override: This is a solution that will work on more or less all heat pumps, but the accuracy of the heat pumps electricity consumption is not as good as for other alternatives. There is also a need for a physical installation on the heat pump which is costly.
2. For premium heat pumps sold today and future heat pumps:
   Indirect control of the temperature settings by adjustments of the heating curve or similar via web-API. Many premium heat pumps sold today are connected to the internet and a web interface or an app makes it possible for the owner to make changes related to the heat pump settings at a distance.
3. For future heat pumps:
   Direct control of the heat pump will give the fastest control of the power consumption and have the best accuracy. To make this happening it needs to be part of the manufacturers standardized protocol for controlling the heat pump.
4. Chose a heat pump with a fast response variable speed compressor. A survey to a few manufacturers shows a built-in limit between 4.5 and 80 minutes to go from compressor off to maximum capacity for heat pumps with variable speed compressors.

Acknowledgements

This article is based on research done within the EU-project Flexible Heat and Power (FHP). The FHP-project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 731231 and includes the following partners: Vito (project leader), Tecnalia, Noda, Honeywell, Ecovat, RISE and Karlshamn Energi.

References

[1] Fisher, D. and Madani, H. (2017) On heat pumps in smart grids: A review. Renewable and Sustainable Energy Reviews 70 (2017) 342-357.
[2] Paterakis et al. (2017) An Overview of Demand Response: Key-elements and international experience. Renewable and Sustainable Energy Reviews 69 (2017) 871-891.
[3] Sweco. (2016) Elkunders möjlighet till flexibel elanvändning: En underlagsrapport till Energimarknasinspektionen. (In Swedish)
[4] Flexible Heat and Power, (2019-10-31) http://fhp-h2020.eu/.
[5] Lund, Per & Nyeng, Preben & Grandal, Rune & Sørensen, Stig & Bendtsen, Maja & Ray, Guillaume & Larsen, Emil & Mastop, Jessanne & Judex, Florian & Leimgruber, Fabian & Kok, Koen & MacDougall, Pamela. (2016) EcoGrid EU Deliverable 6.7: overall evaluations and conclusions.
[6] BWP Bundesverband Wärmepumpe e.V. (2013) Regularium für das Label "SG Ready" für elektrische Heizungs- und Warmwasserwärmepumpen. s.l. : BWP Marketing & Service GmbH. (In German)
[7] Fischer, David. (2017) Integrating Heat Pumps into Smart Grids -A study on system design, controls and operation. Stockholm : KTH, ISSN 1102-0245.
[8] CEN, EN14825:2018. (2018). Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling – Testing and rating at part load conditions and calculation of seasonal performance, Brussels.
[9] Nord Pool. (2018-08-07). https://www.nordpoolgroup.com/.
[10] Danmarks Meteorologiske Institut. (2019-02-21). DMI Vejrarkive, https://www.dmi.dk/vejrarkiv/.