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HARDWARE-IN-THE-LOOP DYNAMIC TESTING OF A NEW CONTROL OF HEAT PUMPS' ACTIVE POWER MODULATION FOR GRID STABILITY

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Abstract

The tests of 3 Heat Pumps (HP) from 3 European manufacturers were performed in controlled laboratory environment, over several days period each. Each HP implemented prototype control rules to modulate its power consumption proportionally to frequency and voltage instantaneous deviations. The outdoor unit is exposed to varying weather conditions—cold, average, and warm—while indoor unit aims to achieve different temperature settings to assess its performance in heating and cooling of a virtual building. The unit's electrical supply is controlled to replicate typical distribution grid conditions, as in system splits and low-voltage scenarios (load/generation imbalances). Voltage amplitude and frequency are monitored alongside thermal variables like thermal power and hydraulic circuit supply temperature to the virtual building. These experiments' showed that current HPs in the market implementing such control offer 1 %/s modulation speed of rated power, insufficient during fast frequency deviations, and feature several off-nominal modes (e.g., defrosting/oil gathering/ramp-up) during which active power modulation is impractical. Nonetheless, reaction speed's improvement areas clearly exist for products under development, gradual modulation of HP active power from local grid measurements is shown feasible and able to support grid in enhancing stability with negligible influence on user thermal services.

1. Introduction

In order to reach the 2050 net zero emission target in Europe, Heat Pump (HP) are taking an ever increasing share in domestic and tertiary heating appliances, including Domestic Hot Water (DHW). Traditional heating process were based either on non-electrical resources (like Gas, Oil or Wood) or on simple and poorly controllable resistive heating.

The European electrical system is changing due to the change of nature of production, going from synchronous to Power Electronics (PE) based generation such as wind and PV, but also due to the change of load type, with Electrolysers, Datacenters on the transmission connected loads, and EV charging, heating.

The question addressed in this paper is the following: How far can heat pumps contribute to electrical grid stability?

Legacy loads such as resistance or motors have been playing an important role in system stability, being sensitive to frequency and voltage of the grid (acting as negative feedback). Such feedback is still assumed in present and future grid stability control schemes while power electronics, that came into most of electrical appliances for energy efficiency reasons for last two decades, made it insensitive.

This paper first introduces why active power sensitivity of load to network conditions is crucial for system stability. Then it presents a scheme to make HP active power sensitive to voltage amplitude and frequency. Then it describes the testing procedure as well as the test-bench used to validate the

behaviour of different upgraded commercial hardware. Thereafter the most significant results of the tests are presented and discussed with regard dynamic performances and limitations. As introduced in section 2, the initial focus of the study was on electrical system stability and resilience, but as ACER proposed a draft version of Demand Connection Code embedding requirement for Limiter Frequency Sensitive Mode Under-Frequency (LFSM-UC) for HP, the conclusion includes also an evaluation of present HP compliance with those.

2. Position of problem and current work contribution

Legacy electrical loads have been sensitive to voltage amplitude and frequency deviation. Its representation for electrical system studies have been and still is a subject for intensive research. From system operator point of view, this sensitivity has been taken into account in system stability management and have even been used to develop specific scheme. Most known example of links between load sensitivity and system stability behaviour are:

- Load self-regulation: in the studies for European frequency stability it is always assumed that load exhibits self-regulation effect, meaning its active power changes with system frequency (between 1 and 2 % active power change for 1Hz deviation). During event taken as design hypothesis for frequency reserve, a loss a 3 GW of generation is considered

usually leading to a frequency drop to 49.2 Hz. This frequency drop (depending on system load and self-regulation parameter) leads to a decrease of the load between 1.2 and 2.4 GW during transient. This has a very positive impact on system behaviour reducing frequency excursion. (cf. various ENTSOE examples in [1])

- the transient stability of synchronous machine highly depends on load's sensitivity to voltage amplitude, with load that are non-sensitive, the transient stability is worsened.

- in case of local extremely high load situation, active power sensitivity can be used by system operators, they might reduce voltage on the distribution level (usually 5 % decrease), leading to a small decrease of sensitive load, which could be sufficient to ride through the high load period [2].

As this sensitivity is decreasing with the penetration of PE based load, this article investigate how HP can be controlled to reintroduce this desirable load behaviour. This sensitivity is made to help the system during stressed or disturbed situations which can be very local. As an example, in case of a system split, two neighbouring cities can end up being in 2 areas (1 over and 1 under -generation), it is therefore of crucial importance to use local electrical measurements to provide the expected behaviour. Therefore solutions based on communication with centralised server would be both inefficient and delaying compared to local information.

The reason for focusing on Heat pumps' case in this work are:

- Rising market share in Europe in replacement of traditional gas burners for heating and resistive heating load (for various reasons to summarize : climatic change, cost of gas, cost of electricity, good efficiency while still flexible on-demand (heating) control, provided grid supply is ensured, compared to intermittent and partial heating load coverage of renewable heat production) [4]

- Share of electricity consumption for heating (space or DHW) is rising in Europe, first electricity consuming service in residential dwelling scope in France [5], including every heating solution type.

Since, in variable speed HPs and chillers the compressor has the highest share of total power consumption whenever running at minimal speed, it is the first component targeted by this work's grid sensitive control.

The ideal behaviour target is linear reaction to instantaneous grid's states deviations. The time response is indeed critical parameter in case of major grid failure [3]. In the perspective of scale-up of individual appliance sensitivity to european grid scope, the deployment strategy would be through:

- regulatory scheme, beyond electricity market participation (flexibility), to cover every HP target appliances

- Not advanced complex control but straightforward purely proportional control aiming at fully predictable, robust behaviour.

The paper will investigate how mass products such as domestic HP could improve system stability, by introducing active power to voltage and frequency sensitivity in the unit's control.

A literature review dealing with heat pump and grid stability topic issued recent works [6], [7], [8], [9]. Briefly, these works investigated partial Hardware In the Loop (HIL) approach about HP participation to grid stability but limited to real power emulation while thermo-mechanical aspects are simulated. In these works, academic power grid labs implemented grid sensitivity features compared to our work where 3 HP manufacturers' implemented on real commercial hardware components from electrical grid supply to heat transfers to real air or water at the real machine boundaries. Our work investigates also broader range of grid sensitivity characteristics with no deadband for frequency, combined with rms voltage sensitivity; max correction range is realistic with regard product. In literature, the objective is to design ambitious Fast Frequency Control (FFC) prototype for HP while this work is primarily to show the current experimental status with regard to FFC with eventual upgrade of existing HP stock and of the next generation product design.

Current work to fill the gap about artificial sensitivity of HP consumption to grid frequency and voltage, from embedded local measurements, for future products and retrofit : feasibility and level of performance (grid's electrical services and user's thermal and energy efficiency services) of such approach on representative heat pump prototypes in close collaboration with Arkteos, BDR Thermea and Groupe Atlantic heat pump manufacturers to develop the prototypes based on 3 samples from common products in current european market stock: two reversible air source air-to-water heat pumps (ASHP) and one ground source brine-to-water (GSHP) heat pump.

3. Methodology

The first phase of the work aimed at enrolling diverse heat pump manufacturers that were able to prototype grid states sensitivity feature on representative HP technologies on the market (France largest national market in Europe [4]) to supply building's thermal services: space heating, domestic hot water (DHW), and cooling in case of reversible ASHP.

- ASHP 8kW_{th} mono-block 2.7kW_e/5.5kW_{th} (-2/57 °C)
- ASHP 6kW_{th} split 2.5kW_e/5.1kW_{th} (-3/55 °C)
- GSHP 12kW_{th} mono-bloc 3.6kW_e/7.7kW_{th} (4/65 °C)

This work's objective is to characterize different HPs, like a black-box system, as an assembly of multiple layers and components from different manufacturers leading to variable level of details about the predictive behaviour whenever design specifications.

1. Develop the grid states' sensitive HP prototypes: Hardware interface with frequency/Voltage measurement device and software grid sensitive

feature (cf. Fig. 1 bottom, in green the prototype's development)

2. Develop electrical supply and thermal test conditions for test plan: Step/ramp response test on electrical side / steady state on thermal side, and realistic response test on electrical and thermal sides
3. Characterize prototypes' behaviours with HIL approach regarding both HP electrical powering and HP thermal services as illustrated in Fig. 1. In purple, the simulated test conditions emulated physically both at thermal and electrical boundaries of the tested real heat pump.

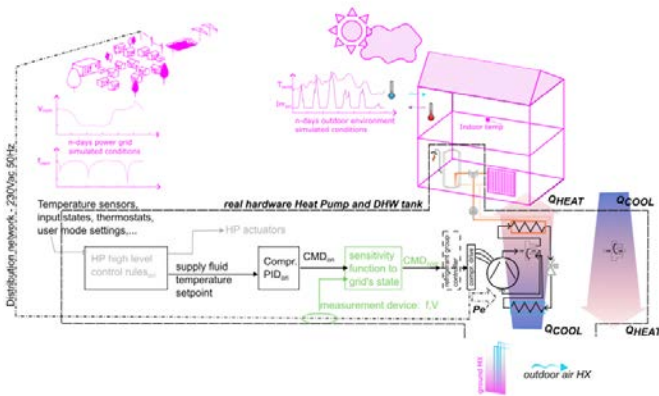


Fig. 1 Experimental test principles and grid sensitivity integration to HP

4. Developments

4.1. Theoretical sensitivity curves

The HP manufacturers integrated into their respective real hardware controller the sensitivity function $f_{gridsens}$ that requests the maximum correction factor with regard to current deviations from nominal states, 50Hz or 230Vrms, as shown in Fig. 2. Each single correction is piecewise linear function, in 3 pieces with maximal power reduction up to 100% for frequency and 10% in 1 piece for voltage. These sensitivities were chosen in order to:

- have low sensitivity for minor frequency deviation in order to have a limited impact on customer for low but frequent frequency deviation.
- have HP almost stopped at 49 Hz, when load shedding usually starts taking place in Europe.
- have a limited impact for voltage deviation, contrary to frequency deviation, low voltage situation can last for several tens of minutes, even couple of hours, to ensure that end user will still have heating source, the power reduction has been capped to 10%.

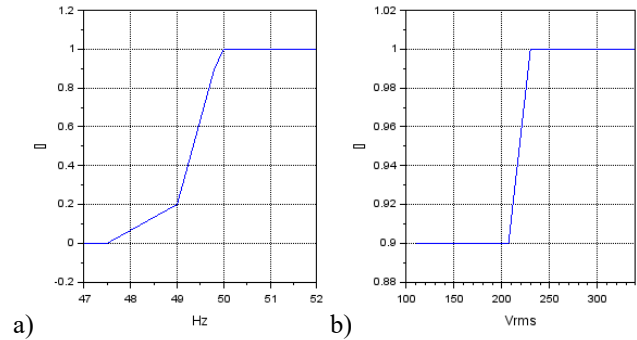


Fig. 2 Corrections factor request vs deviation of a) nominal frequency, or b) voltage – max of both is applied as $f_{gridsens}$

In addition, manufacturers adapted their HP controller interfaces to feed the grid sensitivity software with local electrical measurements at the HP's power supply. Adequate resolutions less than 10 mHz on frequency and 0.2 Vrms on voltage, within 200 ms time resolution, were obtained with chosen sensors commonly available for OEM integrators, SOCOMEC Digiware U module. One manufacturer implemented another sensor Analog Device ADE9153A directly within its control system, reaching similar accuracy and resolution of the electrical measurements.

4.2. Measurements and grid simulator

The SOCOMEC Digiware modules perform the valid electrical measurements every 200ms: It achieves 1mHz resolution and 0.02% accuracy regarding frequency and 0.2% accuracy regarding voltage and active power measurement P_e .

The grid simulator is CINERGIA GE&EL-200 to power each heat pump in single-phase with nominal 230 Vrms at 50 Hz. It achieves 1 mHz resolution regarding frequency in the range 10 to 100 Hz, 0.14 Vrms resolution and 0.3Vrms accuracy in the range 0 to 277 Vrms regarding voltage. The grid simulator is playing electrical test sequences detailed in following section.

4.3. Test sequences

CEA and RTE developed several input test sequences to apply to the real operating HP hardware, both electrical supply and thermal boundaries. On the one hand, the first group is combining different step and ramp input sequences for the grid's states with steady state thermal conditions for heating (air 2°C/water 35°C) and cooling (air 35°C/ water 15°C), as illustrated in Fig. 3. On the other hand, the second group is combining realistic dynamic states profiles both on electrical and thermal sides, as shown in Fig. 4 and Fig. 5. It stands for a stress test sequence during several days, to reveal the HP realistic response in case of several type of critical events in the grid that could happen anytime in the year.

- Step/Ramp input sequences for grid simulator (for frequency in Fig. 3) allowed checking that the sensitivity feature implemented by manufacturers actually match the specified theoretical sensitivity curves in 4.1.

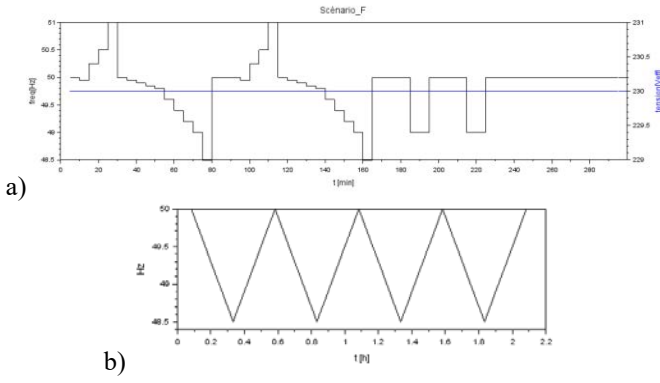


Fig. 3 Input frequency sequences a) steps, b) ramps; constant voltage

- Realistic grid profile, one state every 200ms: the 24h-frequency profile was elaborated from 540s-pattern records by multiple frequency measurement devices located across Europe during two grid system splits in 2021 ([10], [11]) as shown in Fig. 4. These frequency event recording were mixed with low voltage recording at 220V level in order to generate representative data that could be seen by HP connected on distribution grid.

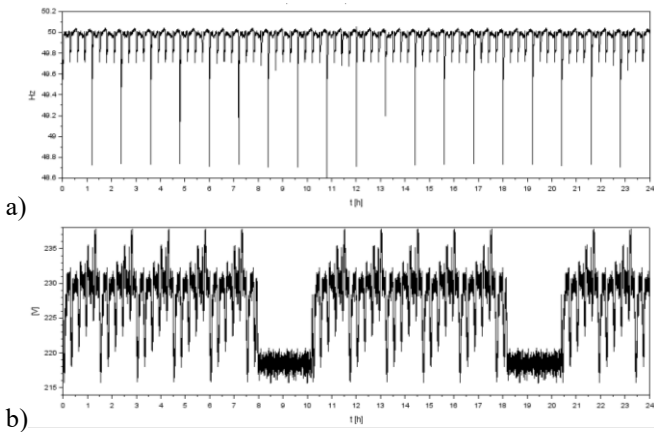


Fig. 4 24h-grid profiles a) frequency, b) voltage

- Realistic 5 days thermal conditions:

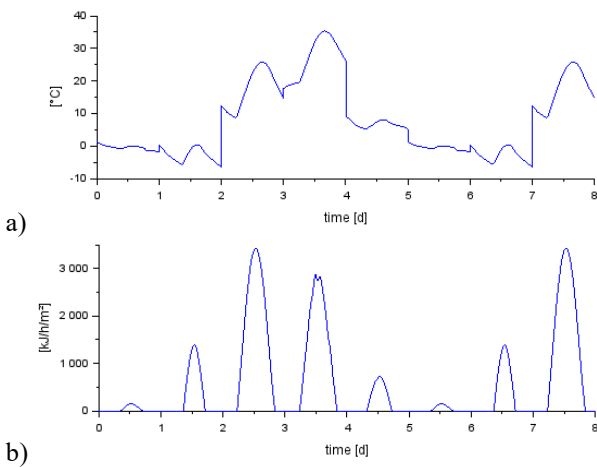


Fig. 5 5-days cycle weather conditions a) outdoor air temperature, b) total horizontal solar radiation

The Fig. 5 illustrates the variation of the thermal conditions applied in the building simulation for the realistic dynamic tests. It aims to mimic the season cycle in 5 real-time days, each standing for winter, hot mid-season, hot summer, cold mid-season and winter again conditions.

Considering all previous test conditions above, CEA performed in total 48 thermal-electrical tests on the 3 real hardware HP prototypes in winter-spring 2024. Since one of the HP prototype manufacturer was able to double and to triple the nominal compressor drive speed rate of change (ROC), it leads to 5 real hardware HP configurations to analyse across the test campaign. Next section 5 is presenting a selection of the main results and observations obtained from the diverse tests following configurations repartition from Tab. 1.

Tab. 1 Selected tests subsets for each hardware HP

Test n°	1,14,15	17,19,26	33,36,38,41 43,44 48	speed ROC x3 x2

4.4. Theoretical correction factor of HP consumption

The Fig. 6 presents a detail of the $f_{gridsens}$ factor ([0;1] range of values) calculated on theoretical 24h-grid profiles (200ms sampling period). In b) the detailed behaviour during the first 540s large amplitude frequency event reveals $-0.5/+0.1 \text{ unit}\cdot\text{s}^{-1}$ range of derivative values.

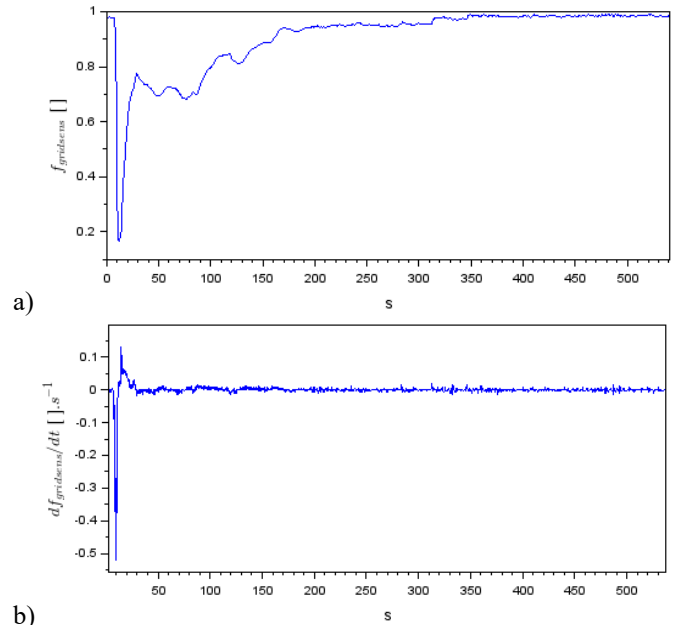


Fig. 6 Details of a) $f_{gridsens}$ factor and b) its derivative, during first large amplitude frequency event

For the analysis of the power measurements variations during grid states deviation events, we introduce $Pe_{theor}(t)$ as the theoretical power consumption assuming immediate reaction of the HP consumption with regard to current correction $f_{gridsens}(t)$ according to the deviation state applied on

$Pe_{ref}(t)$, the nominal power consumption with regard to current thermal service states.

$$Pe_{theor}(t) = f_{gridsens}(t) \cdot Pe_{ref}(t) \quad (1)$$

Considering the typical dynamic of grid deviation events of a few seconds, while the thermal service control's one is rather a few minutes, we assumed constant $Pe_{ref,i}$ during i^{th} grid deviation events (event deviation threshold $f_{gridsens}$ set at $3 \cdot 10^{-3}$) occurring in any test, corresponding to the actual active power consumption at the beginning of the i^{th} grid deviation event. Thus $Pe_{ref}(t)$ is equal to $Pe(t)$ as long the grid is close to nominal states in frequency and voltage, while it is constant $Pe_{ref,i}$ during i^{th} deviation event.

5. Results – Observations – Discussion

5.1. Step and ramp tests

To underline the difference of sensitivity function integration and design of the heat pumps by the manufacturers, the results of ramp tests and step tests are synchronised and normalised in Fig. 7 and Fig. 8. Test 41 is the repetition of the test 33 at compressor driver's nominal speed.

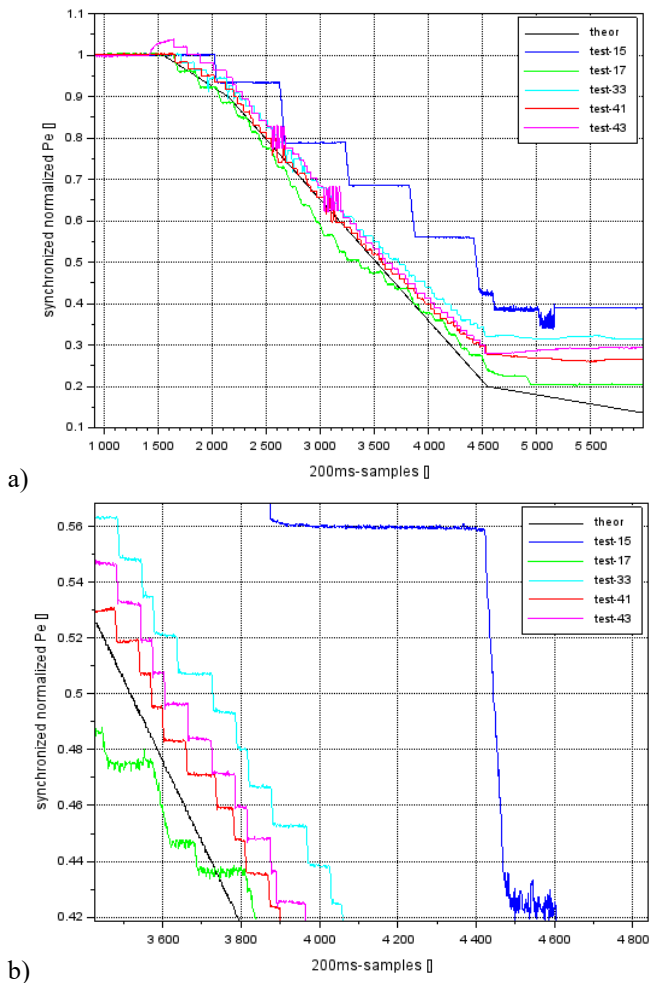


Fig. 7 Frequency ramp tests – comparison 5 HP configurations vs theoretical a) overall, b) details

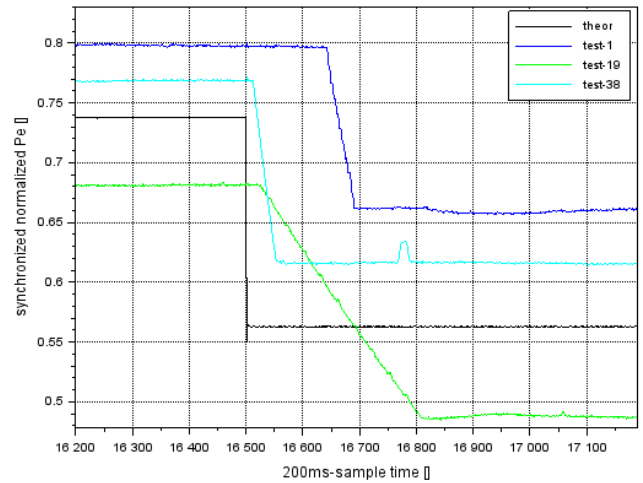


Fig. 8 Frequency step tests detail – comparison 3 HP configurations vs theoretical

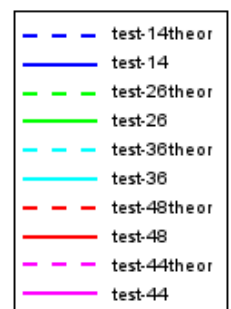
The Fig. 7 reveals similar overall behaviours of the 5 HP configurations in a), following slow variations, while it shows obvious differences in detailed b), in control resolution and overall reaction time of the consumption, from the modulation signal to compressor actual application.

The details from the frequency step tests in Fig. 8 shows different, variable reaction times (28.6+9.6, 5.2+56.6, 2.4+8.0 s) since the theoretical black vertical front and slopes intersections, and different constant consumption's rate of change (absolute slopes: 35, 10, 50 W/s) during compressor speed set-points changes (corresponding to fixed parameter of the compressor drive speed rate of change). We notice that the grid sensitivity reaction time is split into process and communication software times (from grid measurements to the compressor speed drive set point), then actual speed change time of the mechanical compressor. Since the slope is constant, the larger the difference between two states, the longer the actual change time.

Since the grid voltage was set to nominal 230 Vrms during these tests, it also revealed variable voltage drop in the HP's connection lines, due to lines dimensions and actual instantaneous power consumption of each HP. Compared to global value of the frequency over the grid, the voltage locally measured by the HP in the building is actually also relying on its own power consumption in addition to local variations over the distribution grid. Furthermore, we noticed reactive power consumption (power factor > 0.96 typ.) during the power modulation events, to be accounted at distribution grid scope.

5.2. Realistic dynamic tests

Considering the 3 hardware HPs and 5 HP configurations introduced in 4.3, Test 14 and 26 are corresponding to 2 different hardware air source HPs while test 36, 48 and 44 are relating to the same hardware ground source heat pump. Since triple speed is above the compressor manufacturer's



recommended range, this test ran 24h in winter conditions only, compared to more than 5 days for others. For each of these 5 tests, the power consumption is measured and theoretical behaviour is calculated from measurement time series assuming theoretical application of grid sensitivity correction factor on the current reference power consumption, as introduced in eq. (1). The figure hereto shows the curves' legend for the following Fig. 9.

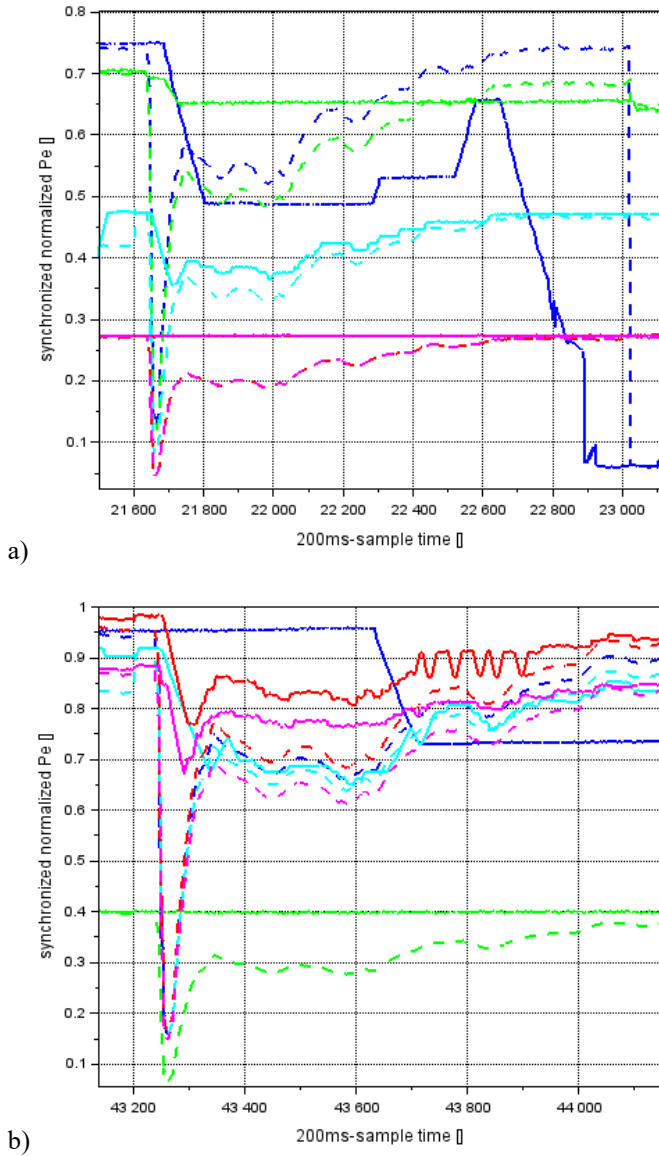


Fig. 9 Two periods' detail of synchronized normalized power consumption of the 5 prototypes in realistic test, winter conditions

Then each measured and theoretical power profile is normalised with regard to the 95% upper threshold from the cumulative distribution function of the measured power along the entire test. Since relying on the same hardware HP, the tests 36, 48 and 44 were normalised with the same value 4083W.

Finally, these tests that ran sequentially on the test bench were artificially synchronized on the electrical test profile time so that we can assume multiple HP units running simultaneously to analyse the various prototypes' power consumption

dynamics in the Fig. 9. It shows that whenever the 5 HP configurations are exposed simultaneously to the same thermal and electrical conditions, their operating states can differ significantly from each other, by design of the usual thermal control. Their dynamic response to grid events differ also, by design of their control system, including reaction time and compressor speed drive ROC parameter. These characteristics are limiting the actual modulation performance as the compressor drive can only follow variations slower than it's own speed ROC. We notice in Fig. 9 b) the highest consumption's derivative of 150W/s in test 44, as expected with the highest compressor drive ROC (3 x nom.) and shortest reaction time. The compressor speed band gaps effect and its command resolution are visible through the oscillations in consumption records in Fig. 9 b).

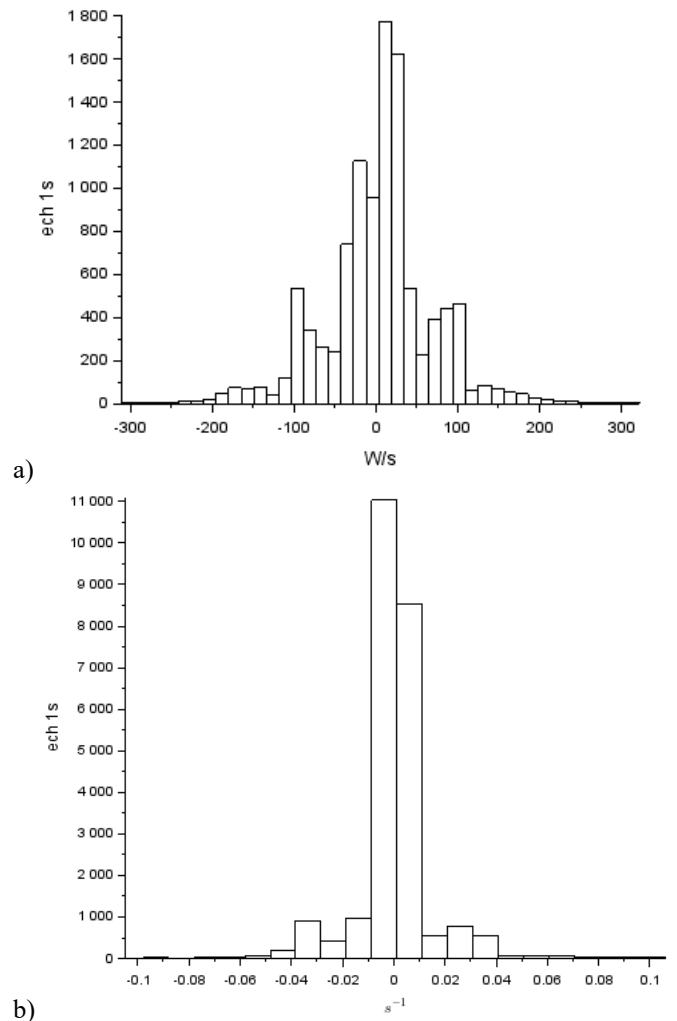


Fig. 10 Test 44 distribution of power derivative a) absolute in $W.s^{-1}$ b) $Pe_{ref,i}$ normalized in $].s^{-1}$

A statistical analysis of the tests results allows obtaining the distributions of rate of change of power in realistic tests, as illustrated in Fig. 10 a) for the test 44, with highest dynamic performance. It confirms observations in the time representation: most of time, the usual HP operation is leading to low dynamic behaviour, with slow ROC. The highest ROCs are observed when they occur in the grid stress test sequence,

a few seconds per hour. The distribution spread between the highest population of consumption ROC and lowest shows that the consumption ROC, even mainly driven by the compressor, depends in less extent from other HP states, like the temperature-pressure operating point and the electronic expansion valve. In Fig. 10 b), beyond normalization of the highest average peak in distribution (~ 150 W/s) by fixed value that leads to 3.6 %/s, ROC is “locally” normalised with regard to $Pe_{ref,i}$ for each successive grid event i , since the reference power consumption is varying across the realistic test sequence. Over the realistic stress test 44, it shows highest power ROC in the range 3-5 %/s.

Considering the test 44 with the best time response and efficiency of the grid sensitivity feature, the Fig. 11 a) shows the cross-correlation $f_{gridsens} * Pe$ (normalized-centered signals) which provides a measurement of the reaction time in complex realistic tests, 5 s, maximal correlation between the two signals. This definition differ from previous one in 5.1. The Fig. 11 b), cross-correlation $f_{gridsens} * T_{BuildingAir}$, shows no residual sensitivity when looking at 540s-pattern of the grid events.

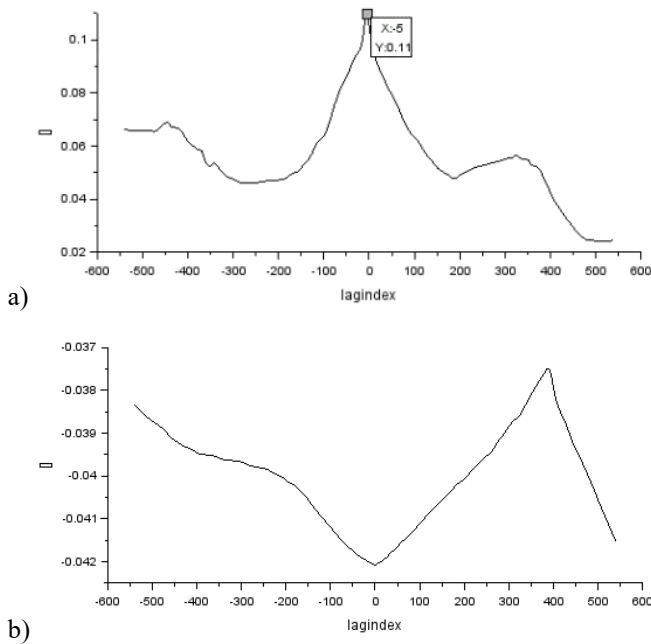


Fig. 11 Test 44 cross-correlation of $f_{gridsens}$ with a) active power consumption, with b) building air simulated temperature - lagindex 1 sec.

During the defrosting cycles (for air source HP only), specific starting, ramp-up and stopping phases (oil recovery, management of the electronic expansion valve), the grid sensitivity controls of the HP was either disabled by manufacturer that actually controls the compressor drive, or inefficient, when manufacturer’s command according to grid was ignored by the outdoor unit that actually controls the compressor drive. In such specific situations compressor is running at minimal nominal speed or below (ramp-up) and modulation with regard to grid sensitivity could affect safety and lifetime of the mechanical subsystems within the heat pump.

Finally, for each of 3 hardware prototypes, the Tab. 2 summarizes the criteria value of typical dynamic response to grid deviations following the realistic stress test sequence developed in this work.

Tab. 2 Power modulation evaluation from realistic stress test

reaction time (s)	98	39	5
rate of change (%/s)	1.0	0.4	2.4

6. Conclusion

Thanks to high-speed local data transmission between affordable tested measurement devices and existing HP controllers, this work confirmed the feasibility for 3 common HPs from the market to monitor locally their actual electrical grid supply, as frequency and V_{rms} measurements with 200ms refreshing time, while respecting the minimal accuracy requirements: 10 mHz and 2.3 V_{rms} . Future products may embed by design such devices at low costs and the external measurement approach with affordable dedicated sensor to the grid state sensitive feature is replicable to retrofit existing HP stock.

Even in the case of large and fast grid frequency deviations followed by circa 5 minutes under-frequency situation in the range 49.6 to 49.8 Hz, the test reveals imperceptible influence on room air temperature.

Depending on the grid sensitivity feature’s level of integration into the existing HP control architecture, varying performance as active power reaction time from 5 to 98 s and active power reduction between 0.4 and 2.4 %/s are observed experimentally. These values depends on the actual content of the realistic test sequence and on the choice of the normalisation approach.

In order to achieve the highest dynamic response, the grid sensitive control had direct access to the compressor speed drive without multiple communication interfaces. On the opposite, for HP that integrated refrigerant cycle on the shelf, including actual compressor and electronic expansion valve controller, the dynamic response regarding reaction time and compressor speed rate of change is limited to the “black box” communication scheme of the refrigerant cycle.

With regard to ACER requirements towards under-frequency situation [12], the modulation speed is currently too low to meet the requirements, compressors’ physical limits is preventing to reach the 300 ms reaction time objective (no active power reduction observed under 4 s). The emergency compressor stop could achieve fast power reduction by compressor shutdown in less than 1 s but above 300 ms including measurement time in less than 200 ms. However, it causes high mechanical stress to the cycle and HP can’t start again before a few minutes, to prevent mechanical aging of the cycle’s components, compressor essentially.

With regard to Rte perspective, this work reveals that the actual power modulation speed from the very diverse HP stock in Europe (confirmed by the 3 sample of HPs in this work) is too low when it is requested to act significantly in less than 1 s, consequences of mechanical inertia of compressor moving part, compared to static power electronic devices in electric vehicles for instance. However, this work also reveals improvement areas of the current commercial HPs towards reaction and compressor drive's rate of change. Looking at grid accidents for instance like in fig. 2.16 and fig. 3.3 from [10] where frequency remains around 49.85 Hz during several minutes, this work reveals that an HP stock with average reaction time of 5 s and power rate of change of 1 %/s could already achieve significant +/-5 % HP stock power modulation in 10 s, as a beneficent reserve to preserve grid stability, with imperceptible effect on thermal service to the building users.

Starting from this work, it reveals some further investigations could be undertaken on similar technology that were not addressed: For air-to-air HP, or HP backup resistive heater (purely static with not moving parts), similar experimental work could extend the results and conclusions on such technologies versus air-to-water and water-to-water HP addressed here. Furthermore, study of the behaviour of a model of HP stock connected to model of european grid, feed by experimental results regarding the dynamic of the models, would allow to draw a realistic dynamic mixed response, in simulation and experimentation on semi-virtual lab.

7. Acknowledgements

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