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"DSO Challenges from introduction of Heat Pumps"

Grid balancing by heat pumps with active-front end rectifiers

Final project report

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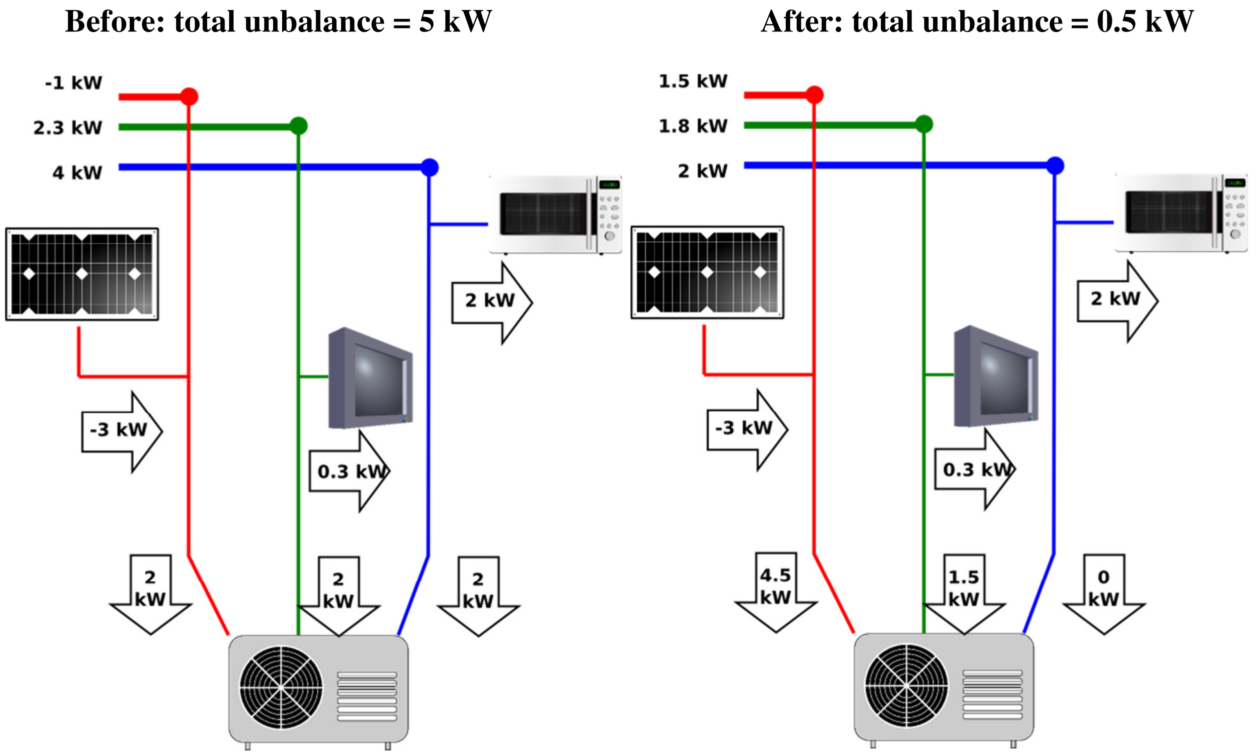
1 Executive summary

Electrification of energy services and solar photovoltaic (PV) power production are central to reducing fossil fuel consumption, but this implies increasing energy flows in the electricity distribution networks. Studies have shown that many residential low voltage (LV) networks are at risk of overload if space heating becomes completely electrified or if PV is installed in a majority of households. If existing trends prevail into the future, LV networks will need to be reinforced to comply with voltage quality requirements. This project has investigated an alternative to existing technology, that modifies appliances improve voltage quality, thereby reducing the need to reinforce LV networks.

Power distribution systems have three phases, and ideally, all three phases are utilized evenly. However, many household appliances, and small PV panels use only one phase, thereby introducing unbalance to the system and reducing voltage quality. When an appliance, such as a heat pump, needs more than 3.5 kW of power, it will be connected to all three phases. Conventional three-phase appliances draw power evenly from all phases, and thereby do not worsen unbalance. This project has asked: can three-phase appliances be controlled not just to prevent unbalance, but to also correct unbalance that arises elsewhere in the system? If a three-phase heat pump draws more power from an under-utilized phase, then the total system unbalance will be reduced, benefiting all customers in the LV network. This concept is illustrated below:



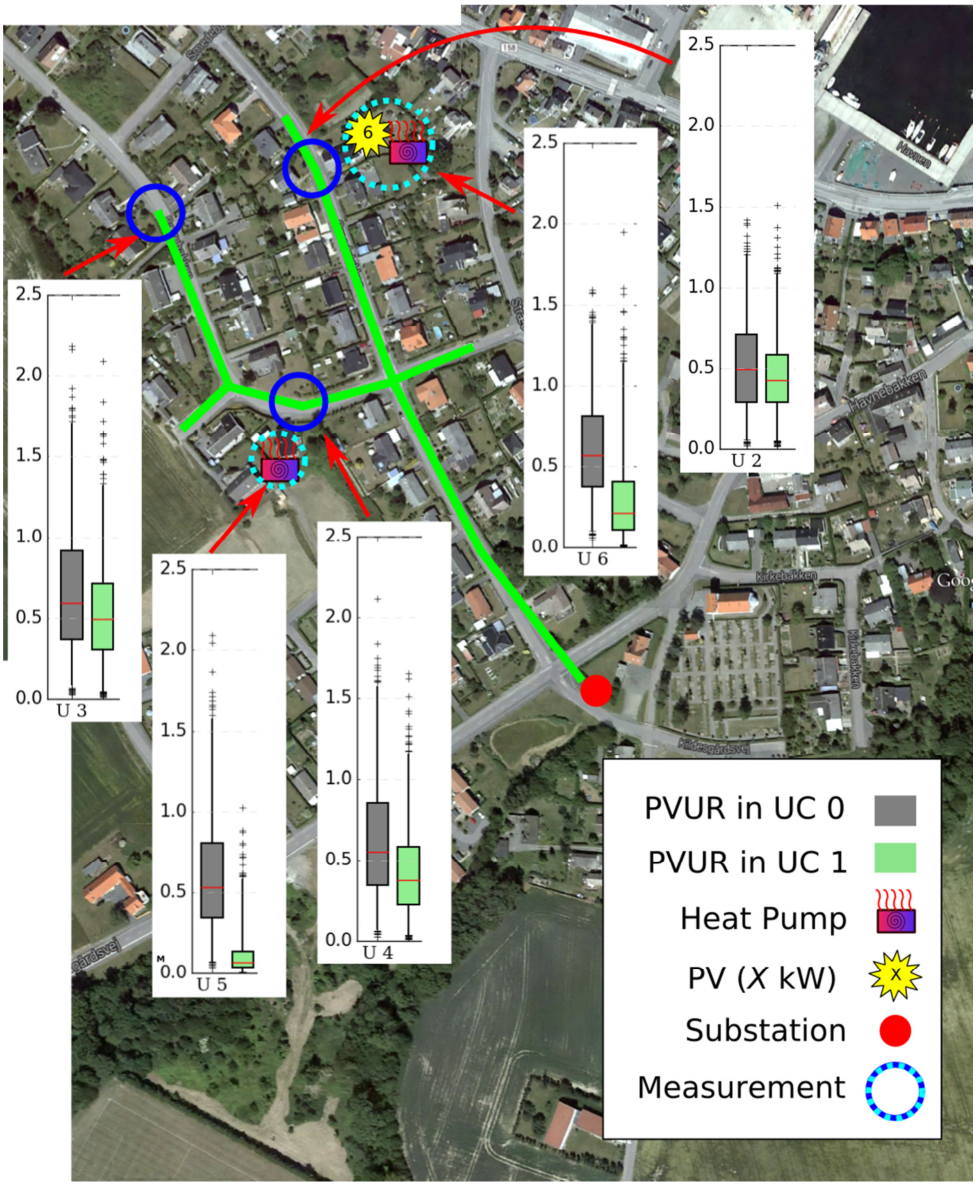
Newer heat pumps regulate their heat production with variable frequency drive (VFD) compressors. These VFDs use power electronics to connect to LV grids, and power electronic "active front-end" rectifiers are the technology which enables the system balancing methods developed and demonstrated in this project. In particular, the commercialization of silicon-carbide devices promises increased performance, and reduced costs, further promoting the spread of power electronic appliances. Note that power electronics are not unique to VFD heat pumps, and the methods described in this report can be applied to other three-phase power electronic devices, such as PV inverters, or battery chargers.

This project has developed novel software control algorithms for a ‘grid-friendly’ heat pump, to enable the heat pump to improve the phase balance in the distribution system. A key feature of all investigated algorithms is that they do not rely on external communications, but instead perform control actions purely based on local measurements. The algorithms were first developed and evaluated using software simulations. Then, prototypes were designed and built using new silicon-carbide components, and these prototypes were tested in a laboratory setting. Finally, field tests of 3 prototypes supplying real residential heat pump loads were conducted. Furthermore, an advanced algorithm using the dq-control abstraction was developed and showed promising results in the lab, but was not deployed in the field test.

The field tests were carried out in central Jutland and on Bornholm. At both locations the project installed data collection devices on the 10/0,4 KV transformers, along the radial and in the households containing the prototype heat pump. The data collection devices have measured unbalances in the net, and gathered evidence to show how the prototypes affect the entire LV feeder.

The results from the simulations and lab tests agreed with each other, and showed that the heat pumps could in most cases eliminate phase-unbalance. However, these controlled experiments did not always give results that were consistent with the field tests. This is discrepancy is explained by saturation of the controllers, irregular active power consumption of the heat pumps, and the dynamic nature the operating power system. What can be concluded with confidence is that, when working properly, **all algorithms reduced voltage unbalance, at the prototypes themselves, and in the feeder as a whole**. The voltage balancing was achieved by increasing the current unbalance at the prototypes themselves, but at the substation, aggregate current unbalance was reduced.

To illustrate the effectiveness of the heat pumps, the following illustration shows the level of voltage unbalance a several locations in the feeder on Bornholm. The base case, “UC0” shown in grey, is the distribution of voltage unbalance (measured as phase voltage unbalance rate = PVUR) without the balancing controller, while “UC1” shown in green is the distribution of voltage unbalance with a balancing controller active in both prototypes.



Variants of the algorithms using active and reactive power were tested. The algorithms using unbalanced active power were more effective than those using reactive power. This is because LV networks are primarily resistive, and active power has a much greater influence on voltage variation.

While previous research has proposed various algorithms for controlling three-phase power electronics for phase balancing, this project is the first to document field trials of such algorithms operating in a live, uncontrolled environment. The results justify further research into how to best control power electronic devices to provide voltage regulation services. Results from only two feeders are insufficient to characterize the performance of these algorithms across the wide range of field conditions that prevail in practice. Furthermore, the behavior of these algorithms under fault conditions needs to be researched before wide-spread deployment can commence.

2 Publications produced during the project

2.1 Peer Reviewed

[A] I. Trintis, P. J. Douglass, R. Maheshwari, S. Munk-Nielsen, ”SiC heat pump converters with support for voltage unbalance in distribution grids”, in *EPE’2015. European Conference on Power Electronics and Application*, Geneva, 8-10 Sept. 2015.

[B] R. Maheshwari, I. Trintis, G. Gohil, S. Chaudhary and S. Munk-Nielsen, "Control of SiC based front-end rectifier under unbalanced supply voltage”, in *EPE’2015. European Conference on Power Electronics and Application*, Geneva, 8-10 Sept. 2015.

[C] P. J. Douglass, I. Trintis, S. Munk-Nielsen, ”Voltage Unbalance Compensation with Smart Three-phase Loads”, *Power Systems Computation Conference (PSCC), 2016*, Genoa, Italy, June 20-24, 2016.

[D] I. Trintis, P. J. Douglass, S. Munk-Nielsen, ”Unbalanced Voltage Compensation in Low Voltage Residential AC Grids”, *IEEE Energy Conversion Congress and Expo 2016,* Milwaukee, USA, Sept. 18-22, 2016.

[E] P. J. Douglass, I. Trintis, “Balancing Distribution Systems with Three-phase Active Front End Rectifiers: Field Experiment Results”, under review for *IEEE Transactions of Smart Grid*.

[F] R. Maheshwari, I. Trintis, P. J. Douglass, “A Novel High Bandwidth Current Control Strategy for SiC MOSFET based Active Front-End Rectifiers under Unbalanced Input Voltage Conditions”, under review for *IEEE Transactions on Industrial Electronics*.

2.2 Other publications

[G] P. J. Douglass, “Varmepumper i lavspændingsnettet”, RA 596, Dansk Energi Forskning og Udvikling technical report, March 2015 [in Danish].

[H] P. J. Douglass, I. Trintis, S. Munk-Nielsen, “Voltage Unbalance Compensation with Smart Three-phase Loads: Proof-of-Concept Simulation Results”, September 2016.

3 Introduction

Danish distribution grid companies (DSO) have for many years planned their 400 V low voltage (LV) grid structure and operation according to well-known parameters and typical load profiles. However customer load profiles, especially in residential areas, are changing as new technologies like PV, heat pumps and electric cars are introduced.

Today, the utilization of the low voltage networks varies from a few tenths of percent up to 70-80 percent depending on:

- whether it is the current or the voltage that are the limiting factor
- the layout and extent of the network
- when the network was built and how the load has developed since then
- how well-balanced the loads are among the three phases
- whether or not distributed generation is fed into the network.

Several DSOs are complaining about that installation of many new PV and heat pumps is resulting in voltage problems, and thereby requiring new cable installations and relating expenses.

New **single-phase appliances** (both consumption and production units) will give rise to **increasing phase unbalances in the grid** which will increase the voltage problems, and hence the costs of grid reinforcement. Single-phase appliances are, in general, less expensive for the consumer than three-phase equivalents, but they shift costs of system unbalance onto the DSO.

The focus in the report is to **investigate the possibility to reduce phase unbalances** and voltage problems in the distribution grid using heat pumps.

3.1 Increased unbalance in the distribution grids

The influence of phase-unbalance on ***additional voltage variation*** is illustrated in Figure 1 for PV. Single-phase and two-phase inverters lead to significantly higher voltage problems compared to three-phase inverters.

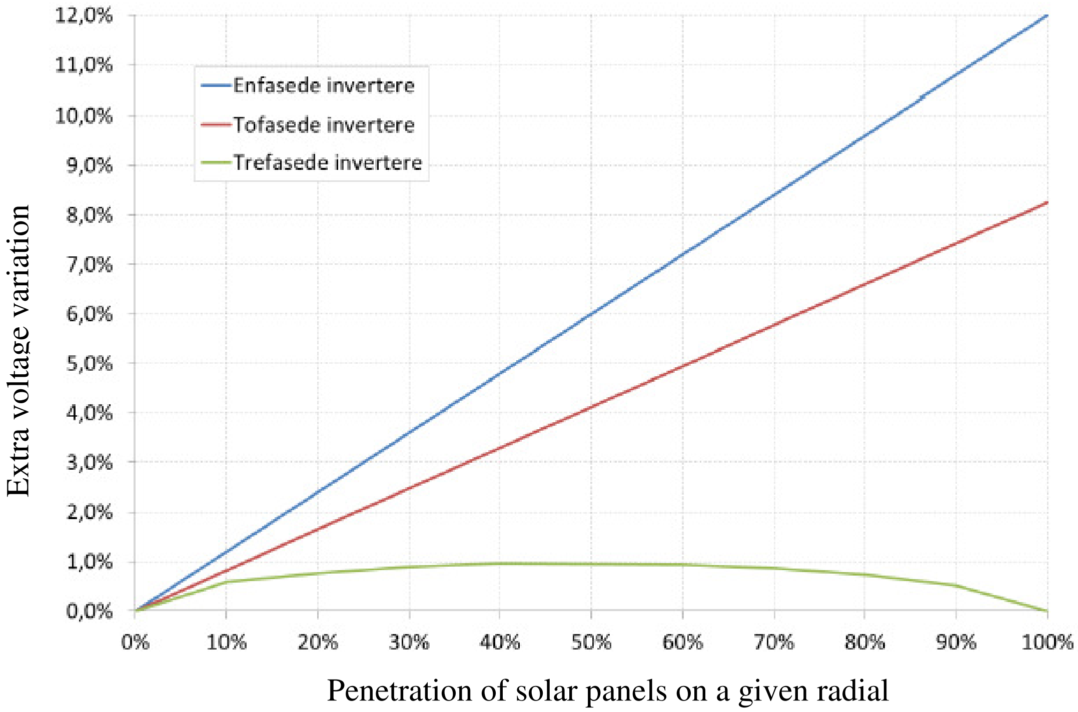


Figure 1. Increased voltage variation in the most sensitive street cabinet as a consequence of asymmetric phase distribution, based on linear extrapolation of effect at 40 % solar penetration. [1]

The impact of other single-phase appliances, such as single-phase heat pumps and EVs, will also increase the demand for reinforcements in the same way as single-phase PV in Figure 1.

Hence, DSOs will have an economic incentive to reduce the phase unbalances (to keep required voltage variation limits), either by ensuring that three-phase appliances are installed where possible or by compensating the unbalances using:

- Installing zigzag transformers to remove zero-sequence voltage
- Installing active filters in the grid
- Encouraging 'grid-friendly' three-phase units at the consumers with active front end rectifiers (e.g. heat pump, PV, battery)

The installation of new consumption and production units in the distribution grid is expected to continue and a large share of these units can be single-phase.

3.2 New consumption and production in distribution grids

Photovoltaics

The increase of the number of PV installations has in recent years changed the traditional load curves for the LV grid, giving rise to challenges of variation in voltage levels and power quality. According to Figure 2 the residential PV capacity is expected to increase even further in the coming years from approximately 0,5 GW in 2016 to 1,2 GW in 2030. Commercial PV and utility-scale PV is also expected to increase significantly from 0,3 in 2016 GW to 1,7 GW in 2030.

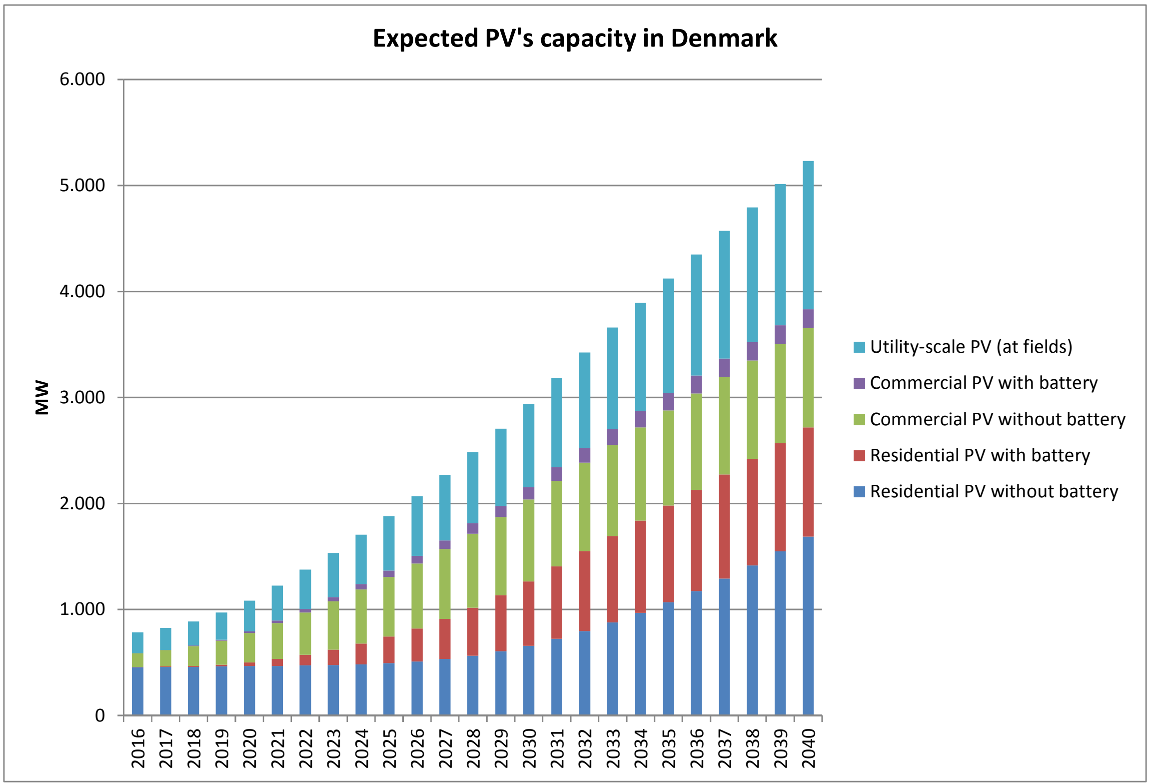


Figure 2. The expected increase in installed capacity of PV in Denmark [2]

Introduction of many PV plants will decrease the minimum load significantly. The voltage variation in a feeder spans the extremes from peak load, to minimum load (or alternatively, peak production). As this span widens, regulating voltage to be within acceptable bounds is a challenge. Overvoltage caused by PV infeed can damage sensitive electronics, and lead to PV curtailment.

Heat pumps

The large-scale introduction of heat pumps to replace oil and gas boilers will also change the typical load curves for the LV grid in domestic areas. The Danish Government has banned the installation of oil and gas fired boilers in new houses from 2013. Replacement of oil boilers in existing houses will soon no longer be allowed, so the house owners will have to find alternative solutions when their oil boilers are worn out. In rural areas without district heating, the most obvious alternatives are heat pumps or pellet boilers.

The expected number and electricity consumption of individual heat pumps in Denmark is shown in Figure 3**Fejl! Henvisningskilde ikke fundet.**. An increase from approximately 80.000 in 2016 to 230.000 in 2030 is expected.

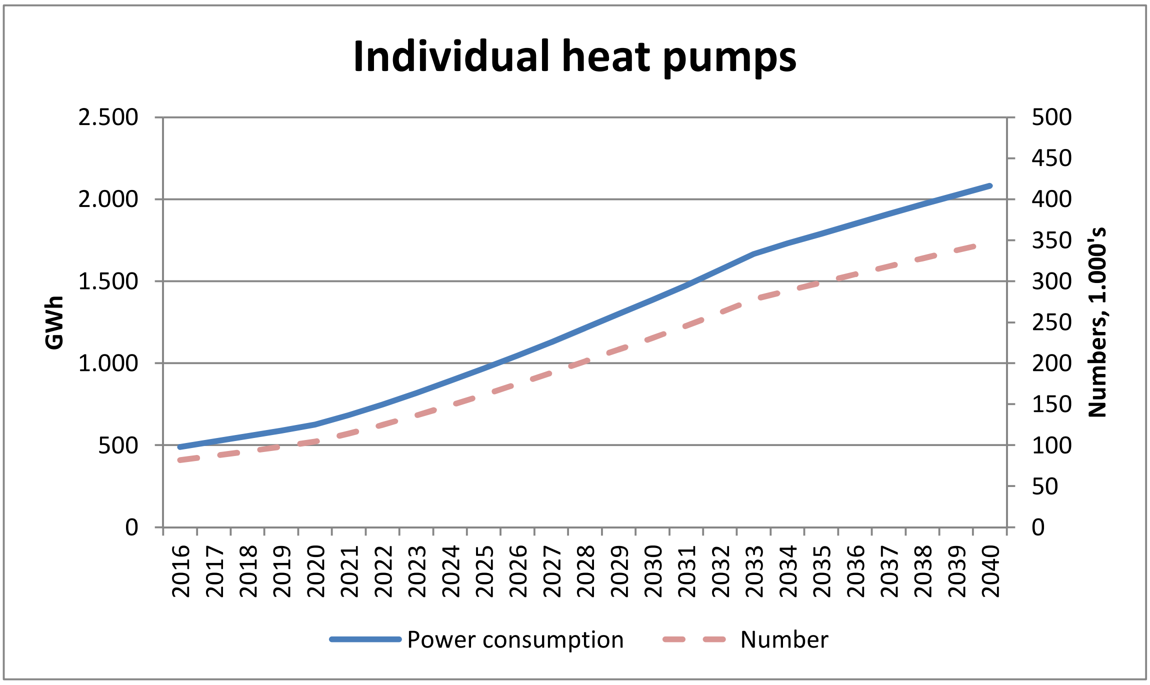


Figure 3. The expected increase in electricity consumption and number of installations of individual heat pumps in Denmark [2]. Number is calculated via 6 MWh power consumption per heat pump.

Electric Vehicles
Electric cars can also change the load profile significantly in LV grids. Approximately 220.000 EV's are expected in 2030 according to Energinet.dk [2].

3.3 Investigated solutions to reduce phase unbalances

By **active control of new and existing three-phase units**, and possibly introducing new capabilities to the grid interface, it will be possible to reduce the voltage variations and level out the unbalance on LV feeders.

In this project, new technical capabilities of individual heat pumps are designed to mitigate the expected **challenges of unbalances in the distribution grid**. However, the solutions will also be relevant to other three-phase units like PV, and battery chargers.

The effect of active control of heat pumps on phase unbalances is illustrated in Figure 4:

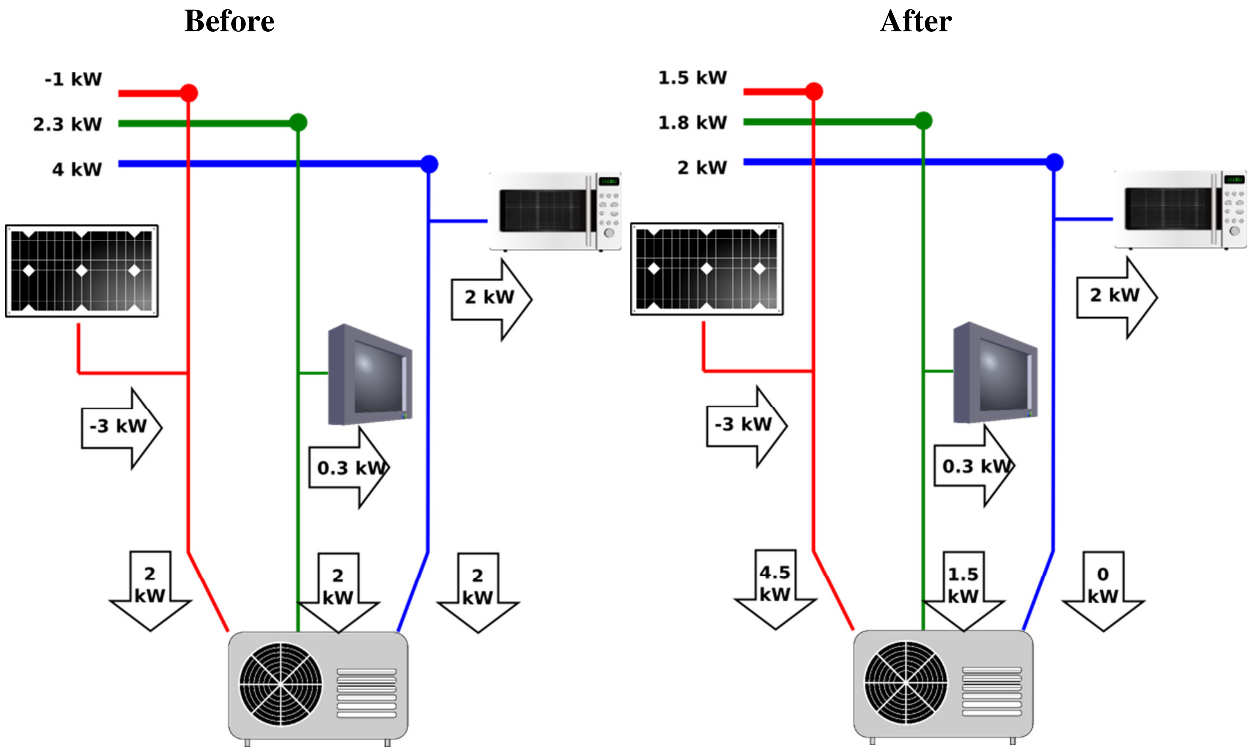


Figure 4. Situation in a normal household with single-phase appliances and a three phase heat pump. (left) without phase balancing (right) with phase balancing via active front end (right). Phase balancing by the heat pump reduces the difference in load between phase 1 and 3 from 5 kW to 0.5 kW.

The figure illustrates how the three phase heat pump with active front end rectifier can help phase-unbalances in the household. Moreover, the active front end can help to balance phase-unbalances in the grid, which is investigated in this report.

3.4 New technology in heat pumps

The focus in the project is on Variable Frequency Drive (VFD) heat pumps which are found in an increasing number of commercial products.

VFD heat pumps offer improved control capabilities, including load shifting, compared to conventional ON/OFF regulated heat pumps.

The new heat pump capabilities developed in the project will work together with commercially available VFD heat pumps. The new technical capabilities require development of:

- **Heat pump converter hardware designed for grid support.** The converter must deliver AC power with varying frequency to a heat pump compressor, while providing grid support on the grid-connected rectifier. The converter is designed using newly available silicon carbide IGBT switching devices. These devices have a higher switching frequency than conventional silicon based IGBTs, which in turn allows for new control strategies described in the project. The goal of using silicon carbide devices is to reduce the cost of passive components (smaller capacitors and inductors in filters), and achieve higher efficiency and power density.

- **Control algorithms needed for grid support.** The developed control algorithms for the heat pump converter will improve the power quality in the grid by reducing the unbalance in the grid by providing unbalance compensation, as well as by improving the power factor.

The possible concepts of a VFD heat pump with new technical capabilities are described in chapter 4.2. In chapter 4.3 the selected and tested concept in this project is explained in further detail.

3.5 Problem statement

This project will focus on the challenges Danish DSOs are facing due to voltage and phase unbalances in distribution grids due to increasing number of PV and heat pumps.
The report will attempt to answer the following questions:

Can three-phase VFD heat pumps with active-front end rectifiers be actively controlled to reduce system unbalance? How large is the balancing potential?

Under which conditions is it likely that active-front end rectifiers can prevent or postpone the required reinforcements? How large is the potential for grid cost savings?

The new concept was demonstrated at real customers during the heating season 2015/2016 in the Danish DSOs TREFOR's and Østkraft's grid areas.

3.6 Out of project scope

The active power consumption of the heat pumps will not be modified by the control methods studied in this project. Numerous other research projects, such as EcoGrid EU, have investigated how to optimize energy consumption for space heating to lower costs, and emissions. Shifting power consumption in time to match fluctuating energy sources will be part of future heat pump operation strategies, but it was not feasible to test during this project. The prototype converters built for the demonstration tested an innovative grid-side connection, but the heat pump side of the converter was unchanged. It was also import to the demonstration participants that they were assured that their home heating system would not be affected by the prototypes.

3.7 Reader's guide – report outline

The project involved simulation, demonstration, and economic evaluation to address the performance and full scale potential of the suggested new heat pump concept.

The remainder of the report is structured as follows:

- The proposed heat pump technical concept is explained in Chapter 4.
- The Use Cases that are defined in the project are explained in Chapter 5. The use cases are defined to quantify the impact of smart active-front end heat pump design compared to business-as-usual rectifier.
- The simulation of new heat pump concept and impact on distribution grid is introduced in Chapter 6.
- A detailed description of the demonstration sites is presented in Chapter 7.
- Results from the lab tests and demonstration is presented and analyzed in Chapter 8.
- The key technical findings are presented in Chapter 9
- The potential for grid reinforcement savings is discussed in Chapter 10.
- Finally, recommendations for future research are discussed in Chapter 0.

4 Technical concept

4.1 Business-as-usual heat pump technologies

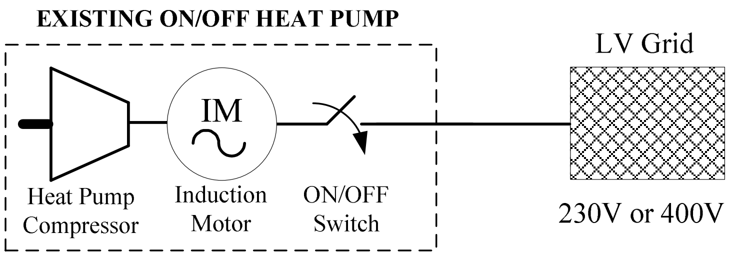
Typically, heat pumps are designed to provide the optimal balance between investment cost and operation cost for the private consumer. Heat pumps are characterized by relatively high investment costs, and low operating costs. Therefore, the current practice is to ensure a large number of full-load operating hours by under-sizing the heat pump. A supplementary heat source, often an inexpensive and inefficient resistive heater, is activated to cover the heating deficit during periods of peak thermal energy demand.

A heat pump (HP) dimensioned to provide 55-60% of peak demand will cover 85-90% of the total annual energy demand. That makes sense for the consumers, but for the DSO, the 10-15 % of heat demand provided by the resistive heater can add to peak load, forcing costly network reinforcement. New building regulations require heat pumps to be dimensioned to cover the full heat load, but this leads to a lower utilization of the heat pump (relative to their nameplate capacity), and this in turn leads to interest in VFD heat pumps which are most efficient when partly loaded.

The state of the art heat pump topologies are shown in Figure 5. The simplest and the most common heat pump has a direct grid connection using an ON/OFF switch, see Figure 5a. The control is usually done using a hysteresis temperature band, therefore allowing a certain variation of the temperature under control which is a bit of a disadvantage for the end user. Moreover, by directly connecting the motor to the grid, the start-up is rough both for the grid and for the motor and compressor – a high startup current being drawn to magnetize the motor (5-7 times the nominal current). Even worse, some are using a single phase power supply (230V),which increases the unbalance in the distribution grid. The unbalance can be further increased if on one of the other phases a single phase photovoltaic (PV) generator is placed.

Some commercial products using the configuration from Figure 5a:

- 230V supply: Bosch AWBS 2-6, 8-15 (2 to 15 kW heat rated) [3], Panasonic Aquarea 3-9 kW (3-9 kW heat rated) [4];
- 400V supply: Bosch EHP 6/7/9/11/14/17 (Heat rated at 6 to 17 kW) [5], Nibe F2025 (6-14 kW heat rated) [6], Danfoss DHP-R (21-42 kW heat rated) [7]



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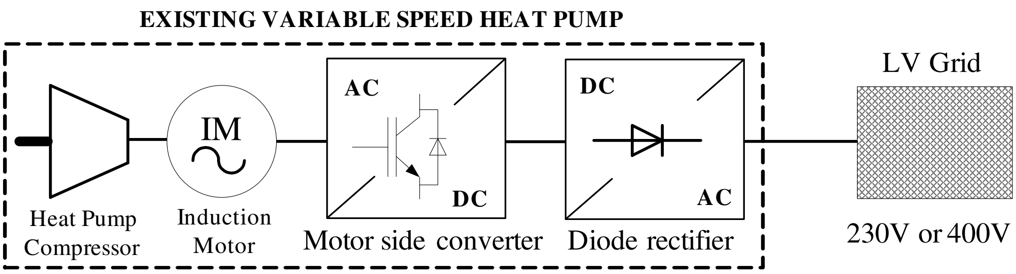


b)

Figure 5. Heat pumps topologies: a) ON/OFF switch b) variable speed heat pumps

An improved heat pump topology is shown in Figure 5b, where a VFD is used to drive the compressor. Using a power converter to control the motor results in a fine control of the indoor temperature, and reduces the mechanical stress of the HP motor and compressor. The startup is soft which in turn helps the distribution grid and improves the reliability of the heat pump. This topology however can also be supplied with one phase, introducing unbalance in the grid. The diode rectifier usually draws a grid current with a low power factor and with a high level of harmonic distortion.

Some commercial heat pumps using the configuration from Figure 5b:

- 230V supply: Bosh Compress 6000 AW 1-faset (5-9 kW heat rated) [8]
- 400V supply: Bosh Compress 6000 AW 3-faset (13, 17 kW heat rated) [8], Nibe Fighter 1250 [9].

Some heat pumps can also help the grid by phase-shifting the load, if they can be controlled via a communication line by the DSO (smart grid enabled HPs).

4.1.1 Challenges due to business-as-usual heat pumps

At present levels of penetration, HPs have not caused disruption of power distribution network operation, but the existing power distribution network will not be able to support a complete replacement of fossil-fueled boilers with the type of heat pumps available today. An example of voltage unbalance measured in Bornholm during the 2014 to 2015 winter is shown in Figure 6. At the time of measurement, the penetration of heat pumps and PVs is however limited, and the power quality is still challenged at some points during the day as seen in Figure 6.

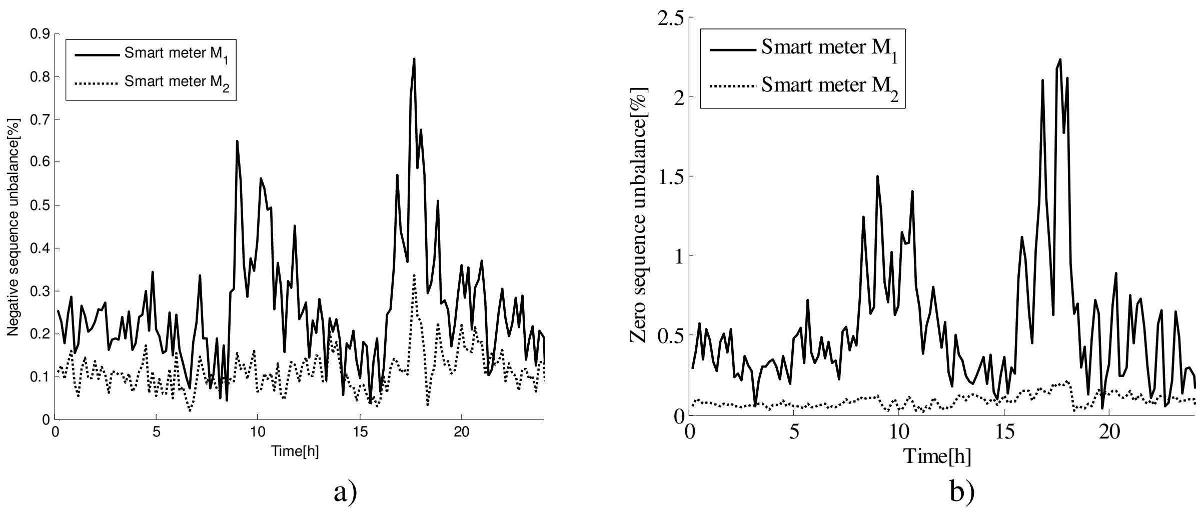


Figure 6. Grid voltage unbalance at low penetration of heat pumps and photovoltaic installations

The magnitude of the zero sequence voltage is also measured and shown in Figure 6b, which is quite significant when compared to the negative sequence. When a significant amount of PVs and HPs are to be installed in addition to this installation, the unbalance in the grid voltages and the zero sequence components will limit the maximum power to be carried by the distribution lines. Therefore, installing single-phase HPs of the type shown in Figure 5 will only make the unbalance worse and limit the maximum number of HPs installations.

Commercially available variable speed HPs (Figure 5b) usually operate at low power factor and increases the voltage harmonic distortion due to incomplete control of the rectifier. These facts will also decrease the quality of the grid voltage further.

4.2 Proposed heat pump concept

To address the challenges highlighted in the previous section, the smart variable frequency heat pump concept is proposed in Figure 7. The variable speed control of the motor that drives the HP compressor is achieved by a DC-AC motor side converter. This control is well known from other appliances (i.e. regenerative drives) and can also incorporate the reference from the DSO to shift the load during peak hours. The new part is on the grid side, where another DC-AC converter is controlling the grid currents and the level of the DC-link voltage. The grid connection will only be to all three-phases and never to a single-phase.

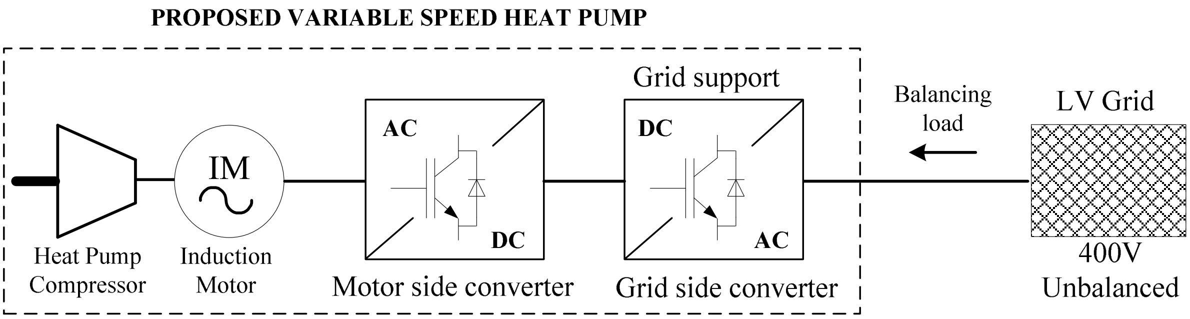


Figure 7. Proposed variable speed heat pump with grid conditioning functions

By having complete control of the grid currents, the heat pump can draw sinusoidal currents at unity power factor and with very low harmonic distortion. Moreover, further services can be provided to the grid such as injection of reactive power, unbalance voltage compensation and eventually the compensation of low order harmonics introduced by other devices in the grid (passive rectifier based consumers).

Where the grid power factor is low, due to a significant amount of inductive loads, the proposed heat pump can be controlled to act as a capacitive load to generate reactive power. The reactive power injected will boost the grid voltage, and therefore improving the power quality.

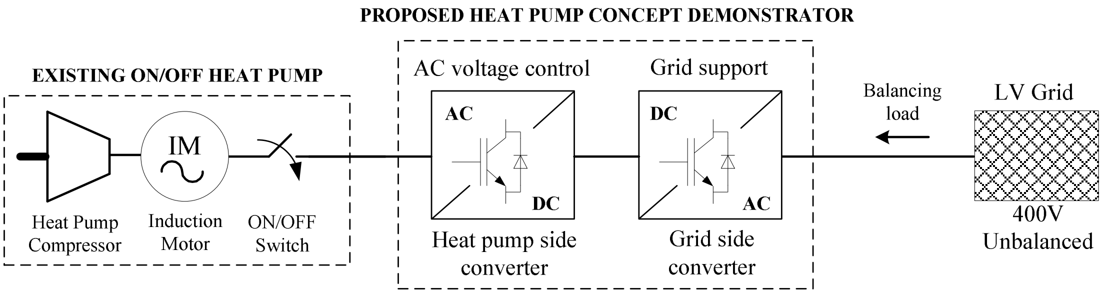
As it was presented in Figure 6, the grid voltage is unbalanced. Drawing currents with different magnitudes from the different phases of the grid can reduce or ideally cancel the voltage unbalance at the coupling point of the proposed heat pump, as it will in the next chapters be described. Depending on the position of the heat pump in the electrical network, it might be useful to draw more or less balancing load currents that will help the distribution grid as a whole. In that case the optimal current references can not to be locally generated in the heat pump controller without external knowledge of the network provided by the DSO.

The power electronics used in the business as usual heat pumps from Figure 5 are built using Si devices. Recent development in Wide Bandgap Devices (WBD) such as Silicon Carbide (SiC) and Gallium Nitride (GaN) are seen as the next generation of switching devices for the power electronic converters used in many applications. SiC devices have the potential to replace the conventional Insulated Gate Bipolar Transistors (IGBTs) which are approaching the theoretical limits of the silicon material. The new generation of MOSFET SiC devices can operate at high temperature (> 300 °C in the junction) and high frequency (hundreds of kHz) with low conduction loss, which can significantly increase power density. For HP applications, the specific interests of utilizing these devices are to improve the conversion efficiency, to develop novel control architectures and to decrease the size of power converters and ultimately decrease the overall cost.

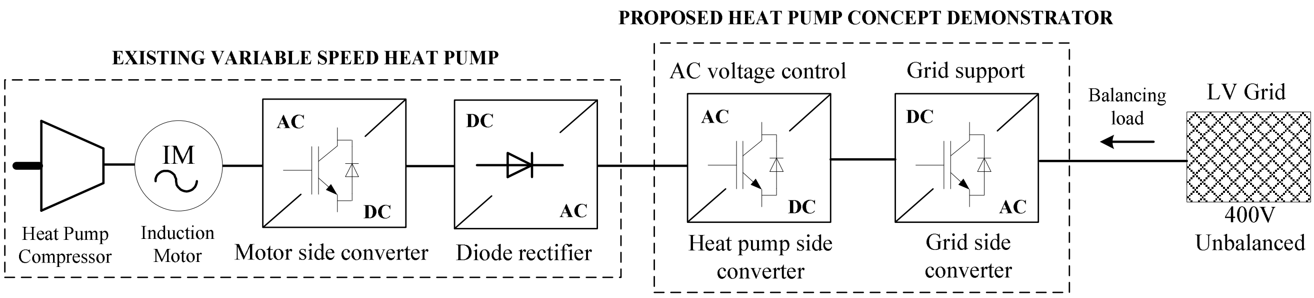
4.3 Demonstration of the proposed concept

Initially, the demonstration of the proposed heat pump concept was planned to have involved the modification of an existing HP concept. For that purpose, the involvement of a heat pump manufacturer was necessary. It was unfortunately not possible to get the involvement of a heat pump manufacturer in the project; therefore the exact concept presented in Figure 4 could not be demonstrated.

To overcome the aforementioned limitation, and still be able to demonstrate the potential of the proposed concept, the demonstration solutions are shown in Figure 8 for both types of existing heat pumps. The AC/AC back-to-back converter that is proposed for the heat pump concept from Figure 7 will be placed in series with the existing HP available at the customer. The heat pump will be provided with its rated grid voltage parameters (230V or 400V, 50Hz) by the “Heat pump side converter” (the “Motor side converter” from the proposed concept), while the aforementioned grid support functions will be implemented in the “Grid side converter”.



a)



b)

Figure 8. Demonstrators of SiC based heat pumps: a) Back-to-back compensator for ON/OFF switch heat pumps; b) Back-to-back compensator for VFD heat pumps

The limitation when using the demonstrators from Figure 8 is the demonstration of the load shift. That is because the access to the temperature controller of the heat pump is strictly forbidden, because of the loss of warranty and lack of support from the manufacturers.

4.4 Controls for the proposed concept

The proposed heat pump concept consists of two power converters, as shown in Figure 7, which can each be controlled to achieve the required task. Thus we can split the control problem in two, the control of the heat pump side converter and control of the grid side converter.

The heat pump side converter is controlled with conventional algorithms found in many motor drive products on the market nowadays [10]. Furthermore, on top of the classic motor control, specific load shift can be implemented at the customer to achieve different goals. It has been shown that the heat pump load can be shifted in time with up to 2 hours while maintaining the customer's house temperature within a ±1.5 °C away from the given reference [11]. That can be used, on one hand to, decrease the price paid for electricity by the customer and increase his return on investment, and could be used also to help the grid by making use of the available flexibility of that load.
The control of the grid side converters to maintain a stable DC-link voltage is fundamentally mature, with slight refinements being introduced nowadays [12]. In this project, the grid side converter is controlled not only to deliver energy to the load, but also to provide support to the power supply to reduce voltage unbalance, in this way optimizing the whole power system, including the load and supply network.

4.4.1 Proposed current control for grid voltage unbalance compensation

The key component that can enable grid support algorithms is the grid side converter. Having control of the grid currents, in magnitude and phase, and assuming a high enough load power, the quality of the grid voltage can be improved.

A grid with unbalanced voltages has differences between the magnitudes of the three phases. Therefore, to be able to have a positive impact on the grid voltages the grid converter must be able to flexibly control the active and reactive power that flows in each phase of the three phases. Two control strategies were investigated, one in the rotating *dq* reference frame [B, F] and another in the stationary *abc* reference frame [A, C, E].

dq control scheme

The proposed *dq* control scheme is detecting an oscillation given by the unbalance of the grid voltage and uses it as feedforward to control unbalanced load currents. The rotation of the three-phase unbalance part of the grid currents will be in opposite to the rotation direction of the grid voltage unbalance part, so the converter load currents should balance the grid voltage. The control is implemented with a proportional gain on the feedforward signal, which amplifies the detected unbalance in the grid voltage to generate higher compensating unbalanced currents. The maximum limit of the feedforward gain is limited due to stability reasons, and unfortunately it depends on the level of the grid impedance – the controller can easily create instability issues when deployed in weak grids. Moreover, the compensating power between the unbalanced voltage and compensating unbalanced currents consists of active and reactive power. Since the same currents are used to control the DC-link voltage between the two power converters, a high level of reactive power can lead to instability of the DC voltage control. For the two mentioned reasons, it has been decided not use it for the demonstration. It was however implemented in a prototype and tested in the laboratory [F].

abc control scheme

The proposed *abc* control scheme can allow the grid converter to independently control the grid current on each phase. It will also be desirable to control both the active and reactive current on each phase. The way the current references are generated is the key. Three main goals are to be achieved by the controller:

1. Enable the control of the DC-link voltage by drawing active currents
2. Control the share of active current between phases
3. Control the share of reactive current between phases

The above mentioned goals can be achieved by implementing control variables in the *dq* to *abc* transformation (Park transformation), with the current references given by:

$$i_x = k_x \cdot [i_d \cdot cos(\theta_x) - i_{q,x} \cdot sin(\theta_x)] \quad (1)$$

Here, x is the index of the current phase (A, B or C), k_x is a factor that can change the current distribution between phases, i_d is the active current referece requested by the DC-link voltage controller, θ_x is the angle of the grid voltage for the phase x (detected using a synchronization algorithm), and $i_{q,x}$ is the reference reactive current for the phase x. Thus, the first goal to control the DC-link voltage is achieved by adjusting the active current reference i_d common to all phases. The second goal is achieved by adjusting k_x to be different for the different phase ($k_x = 1$ for balanced load currents). The third goal is achieved by setting different reactive current references $i_{q,x}$ on the different phase with the assumption that $k_x = 1$.

The implemented configuration is in a three-phase three-wire system, therefore it has the following limitation: the sum of all phase currents must be zero at any time. However, even with this limitation, it has been shown that with the proposed *abc* control it is possible to have the highest impact on the grid voltage when the whole load power consumed by the converter [C, H].
It is now possible to develop grid voltage control algorithms that can output phase balancing factors and reactive current references to the proposed current controller.

More details on the control and converter prototype can be found in Appendix 12.

5 Use Cases

In the project Use Cases are defined to quantify the impact of new heat pump design compared to business-as-usual.

The simulation and demonstration are made according to the defined use cases.

5.1 Use Case definition

The defined use cases are:

	Simulation	**Demonstration**
A. Baseline (BaU)	situation with on/off control	Use case 0
1. Local balancing Active power		
B. phase to neutral balancing	See [C]	Use case 1
C. phase to phase balancing	See [C, H]	Use case 2
2. Local balancing Reactive power		
D. HP provide reactive power based on local voltage measurement (phase to neutral)	Not simulated	Use case 3
E. HP provide reactive power based on local voltage measurement (phase to phase)	Not simulated	Use case 4

Table 1. Use case overview

The demonstration use cases summarized from Table 1:

Output \ Feedback Signal	**Phase-Neutral RMS U**	**Phase-Phase RMS U**
Unbalanced Active Current	Use Case 1	Use Case 2
Unbalanced Reactive Current	Use Case 3	Use Case 4

Table 2. Summary of alternative balancing algorithms

5.2 Use cases for demonstration

Based on the proposed control algorithms introduced in section 4.4, four use cases have been chosen for demonstration, with the block schematics shown in Figure 9.

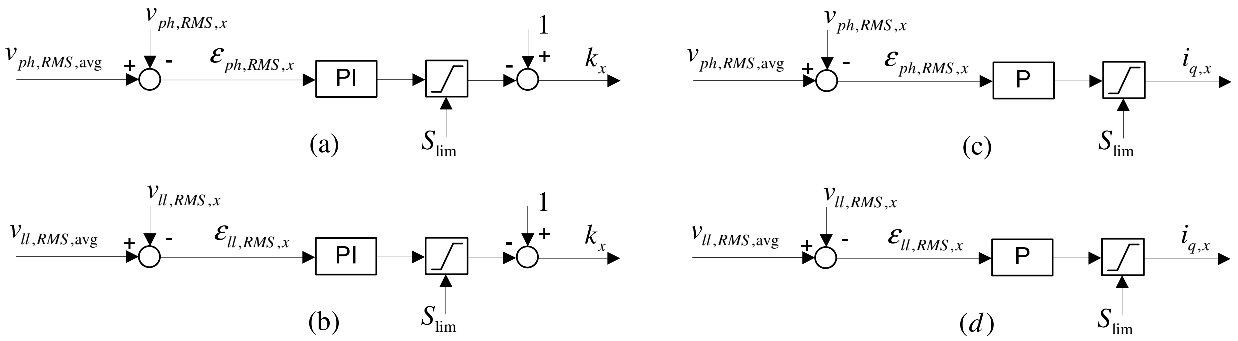


Figure 9. Use cases for demonstration: (a) Use case 1; (b) Use case 2; (a) Use case 3; (a) Use case 4.

A fifth use case (called 'use case 0') is used to have a baseline reference that can be used to quantify the improvement while using the four demonstrated use cases.

The use case and connection to the heat pump used for demonstration is shown in Figure 10

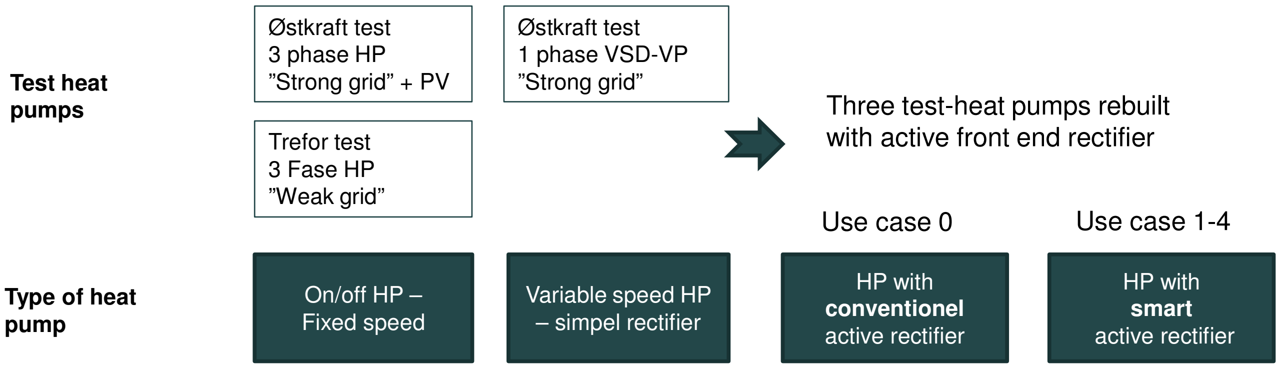


Figure 10. Heat pump types before and during the demonstration.

There are 5 use cases to be demonstrated, and the converter will be preprogrammed to rotate between each use case. The sequence of the preprogrammed use cases will be **A**-B-C-D-E-**A**-B…etc. Measurements are taken using both the sensors in the converter, as well as PQ meter located at strategic locations in the feeder. The PQ meter is storing the average value of voltages and currents every minute. The converter is sampling data with high frequency (50 kHz), but instantaneous samples are stored only every 10 seconds from each prototype. The converter also provides a time stamp and data about which use case is active. Using the timestamp, the converter and PQ measurement data can be coordinated.

Use case 0 – Consumption of balanced currents with unity power factor

Balancing factors are $k_x = 1$ (from eq. 1) and load currents are in phase with the voltages, namely $i_{q,x} = 0$. It must be noted that the operation in this use case is an improvement compared to the standard uncontrolled rectifier (HP from Figure 5b) which has low power factor and high distortion.

Use case 1 – Balancing of phase voltages using active current

The deviation of each phase voltage from the average of the three phases will determine the input error to the unbalance voltage controller, see Figure 9a. Proportional integral (PI) controllers adjust balancing factors for all three phases, adjustment is limited by the saturation block that ensures the converter rated power for one phase is not exceeded. Ideally the HP should eliminate the PVUR at the point of common coupling (PCC).

Use case 2 – Balancing of line voltages using active current

The deviation of each line voltage from the average of the three phases will determine the input error to the unbalance voltage controller, see Figure 9b. The HP should eliminate the VUF at the PCC, considering the controller does not enter saturation.

Use case 3 – Balancing of phase voltages using reactive current
The deviation of each phase voltage from the average of the three phases will determine the input error to the unbalance voltage controller, see Figure 9c. The proportional (P) controllers adjust the reactive currents for all three phases, adjustment is limited by the saturation block that ensures the converter rated power for one phase is not exceeded. The integral term is avoided due to stability reasons. The HP should reduce the PVUR at the point of common coupling (PCC), complete elimination is not expected due to the steady state error always present at the control input in the absence of an integrator.

Use case 4 – Balancing of line voltages using reactive current
The deviation of each line voltage from the average of the three phases will determine the input error to the unbalance voltage controller, see Figure 9d. The HP should reduce the VUF at the PCC.

6 Simulation results

This project will demonstrate the benefit of using power electronics in variable speed heat pumps to improve phase balance in low voltage power systems in live field deployments. But before they are deployed, as part of the process of designing and implementing the devices, simulation studies are used to evaluate the effect of the devices on the power system. The simulations also allow us to evaluate design alternatives and load scenarios that are not feasible to demonstrate within the constraints of the field experiment.

Three different simulations studies were conducted, each of which illuminated different aspects of the challenges DSO face when integrating heat pumps into unbalanced LV networks. The first simulations, described in detail in the next section considered detailed models of the heating demand from conventional heat pumps, and found the effect of this demand on the technical performance of the LV network. Then, the new controller concept was simulated in a relatively simple load flow setup, described in section 6.2. Finally, the most detailed simulations, which modeled the switching behavior of the active front end rectifier, were conducted. These build on the scenarios from the earlier load flow simulations, and are described in section 6.3.

6.1 Heat pump system simulation

These simulations combine models from two technical domains: the thermal domain of the household heating system, and the electrical domain of the power distribution system. The thermal models of households result in an electric energy demand that must be delivered by the power system. The power system model allows us to analyze the impact of the load on component loading, and voltage levels.

The simulation parameters are chosen to create a worst-case scenario of very cold weather (down to -15^{o}C), on days with very high electricity usage (Christmas Eve). The assumption is that if the power system can deliver the energy demanded in this extreme situation without being overloaded, then the power system can also handle all other load scenarios.

Parameters for the electrical network are based on the district on Bornholm, Tejn, where the heat pump demonstration will take place. The entire LV distribution system under the 10/0.4 kV substation is included in the model. All of the houses in the district are assumed to get all of their space heating, and hot water from heat pumps. Parameters for the household models are based on data from the houses that participated in the "Styr Din Varmepumpe" experiment [13].

The simulations are implemented in the software DIgSILENT's Power Factory. Power Factory is a tool optimized to facilitate power system analysis, so the thermal household model had to be created with Power Factory's scripting interface.

Alternative scenarios are constructed from plausible variations of heat pumps design and power system development. The scope of these alternatives is broad, considering the effect of heat pumps in general, rather than only focusing on the use cases addressed in the project demonstration.
The scenarios are evaluated by comparing the minimum voltage levels delivered to the customers, and by comparing the maximum loading the 10/0.4 kV transformer and the cables located closest to the transformer.

One limitation of the study is to only consider a situation where all households use only electricity for heating. This method prevented analyzing the value of unbalance compensating variable speed drives in deferring grid reinforcement.

The full simulation results are found in the technical report RA596 [G].

To summarize, the report found that the existing LV distribution cannot support a complete electrification of space- and tap water heating. Especially, voltage constraint violations limit the network capacity. Besides efforts to reduce the peak energy demand, such greater energy efficiency, the power factor of the heat pumps was identified as a key parameter. With such a large aggregate heat pump load, small differences in their power factor had a significant effect on the system voltage.

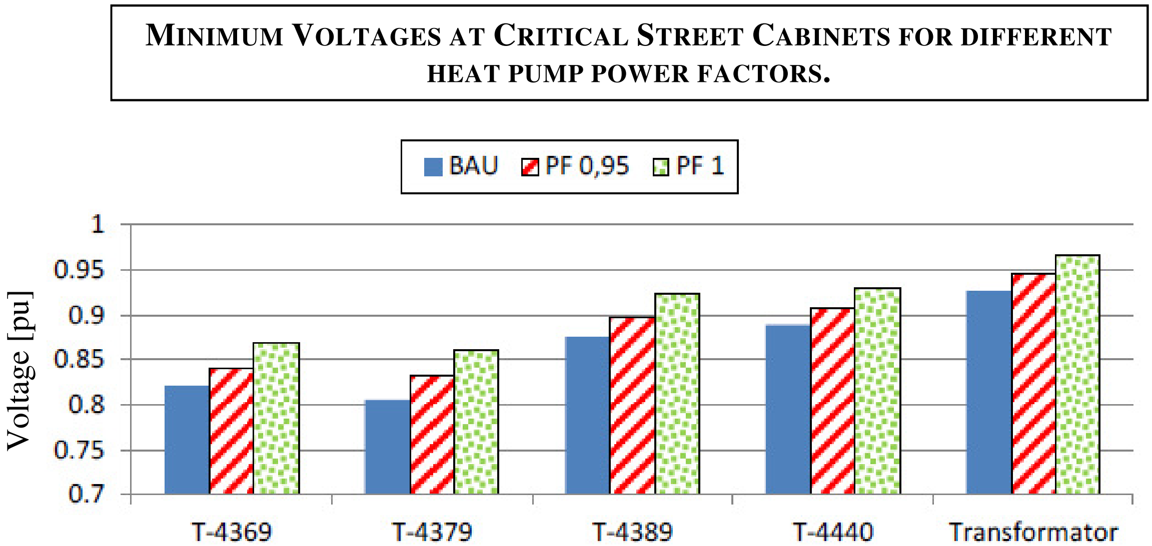


Figure 11. Minimum simulated voltages at the 4 street cabinets at the end of each feeder branch with varying heat pump power factors. BAU is the power factor of a directly connected induction motor, assumed to be 0.85. BAU represents PF 0,85. T-4379 corresponds to measurement point 3, shown in the next section.

This study supported the argument that variable speed drive heat pumps, with an AFE rectifier are the only heating system that can combine both the highest energy efficiency, and high power factor. Thereby, AFE heat pumps can defer LV network upgrades, and have great value to DSOs.

6.2 Proof-of-Concept Load Flow Simulations

Before implementing the voltage balancing algorithms described in section 4.4.1 in hardware prototypes, simulation results were desired. The first simulations were created in PowerFactory, the same simulation tool used to model the distribution system with heat pumps. Because of limitations in PowerFactory's load models, it was infeasible to simulate the *dq* control, only the *abc* control, using P-P RMS voltage as a feedback signal was simulated (use case 2). These simulations are described in detail in [H], a paper that was originally prepared for a conference, but remained unpublished when the conference was cancelled.

The simulations validated the central heuristic of the controller design, but doubts remained as to whether the load model accurately reflected the real behavior of the AFE rectifier.

6.3 Power Electronics System Simulation

During development of the prototype, the simulation software PLECS was used. This software models the circuits in the rectifier based on the state of each of the 6 IGBT switches. The voltage across the DC-link is modelled, as well as the passive components in the input filter. The only electrical features not modelled in the simulator were the transients which occurred during the few nanoseconds when a switch changed state.

The simulator was used when developing the embedded software used in the prototypes. The control software from the simulation could be downloaded directly into the prototypes with minimal changes. Both the outer voltage balancing control loop, and the inner current controller were simulated. Therefore, this simulation environment gave the most credible predictions of the prototype behavior.

Simulation were performed that used scenarios similar to those used in the load flow simulator (section 6.2). These new simulations confirmed the effectiveness of the algorithms, under heavily simplified network conditions. The full results of these simulations are found in [C], which was presented at the *Power System Computation Conference* in June 2016.

These simulations found a trade-off between balancing P-N voltage, and reducing the negative sequence voltage. In the simulations, when the controller removed P-N voltage unbalance, the negative sequence voltage was barely changed, but when removing the negative sequence voltage, the P-N voltage unbalance was reduced by about 50 %.

7 Demonstration description

7.1 Demo site selection

The demonstration concept, described in sections 4.3 required that the test participants already had a heat pump installed in their house. This limitation was chosen to minimize the cost of the demonstration.

Candidate demonstration sites were chosen so that the test participants were located on feeders serving primarily residential customers. Sites with a low short-circuit current (and thus, a high network impedance) were preferred because these feeders are more likely to experience voltage quality problems, and because these feeders will show the largest change in voltage as a result of the heat pump demonstration.

Customers located far from the distribution transformer are preferred. Customers located close to other customers are preferred so that the effect of the heat pump on the power quality of neighbors can be measured.

The pool of candidate customers was rather small, and the final locations did not always live up to all of the criteria of an ideal test site.

7.2 Demo site description

Tejn, Bornholm

The demo site on the north of Bornholm is a small harbor town, with a 10/0.4 kV transformer that serves about 120 households, as well as a church, a kindergarten, a water pumping station, and street lights. Of the households, 11 use electricity as their primary heating source: 2 have resistive heaters, the other 9 have heat pumps. Eleven households also have solar PV generators, two houses had both PV generation and a heat pump. The load is divided among 4 feeders, with feeder #2 having the highest load (relative to the cables' rated current carrying capacity), and feeder #4 having the lowest load.

Two households with heat pumps were found to participate in the demonstration. They can be seen in the aerial photo in Figure 12, and schematically in Figure 13.

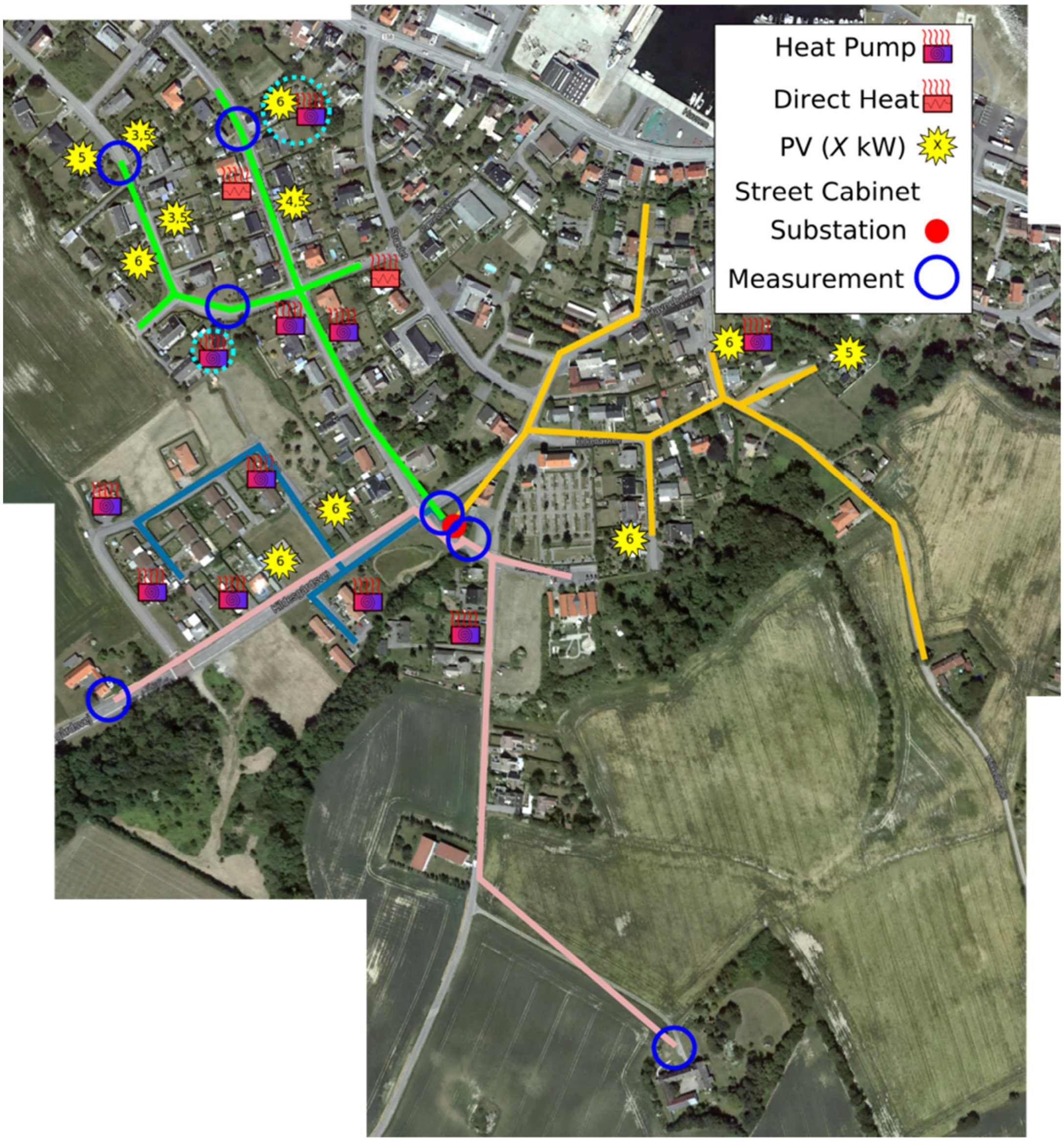


Figure 12. Demonstration site on Bornholm, with existing heat pumps, PV installations and measurement points. Prototypes were installed at sites are shown with dashed light blue circles. [photo source: Google Maps]

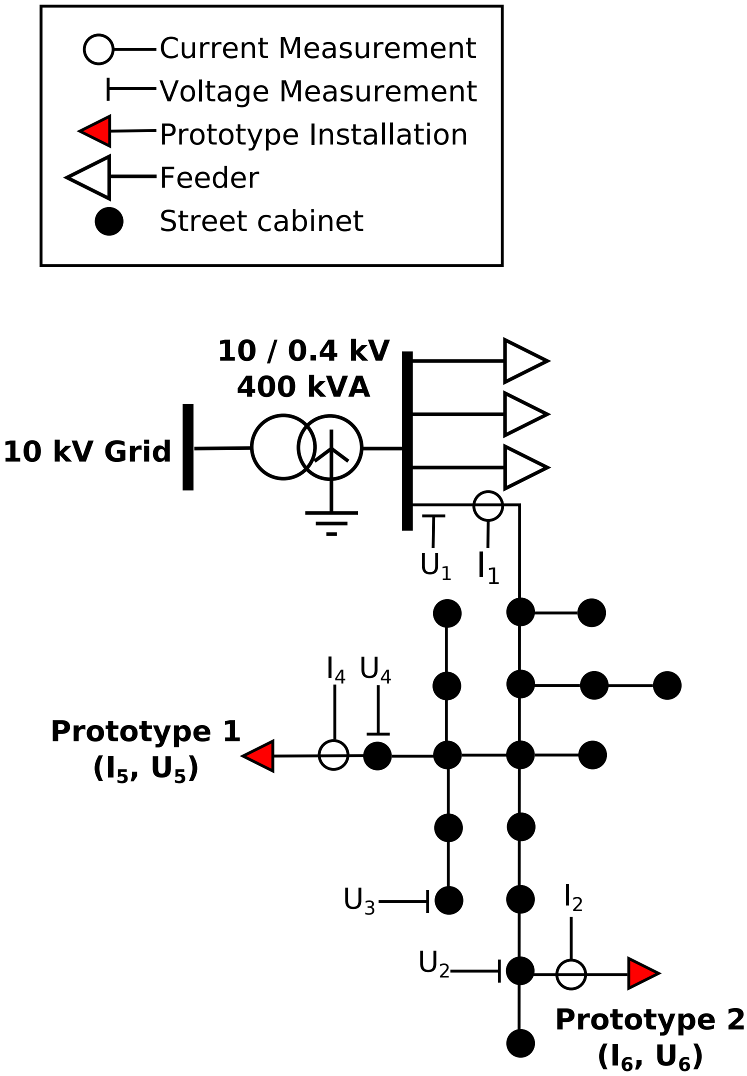


Figure 13. Schematic diagram of Bornholms test site, with the locations of prototypes and PQ measurement devices.

TREFOR, Central Jutland

The ambition was to find two sites in Jutland for demonstration. It was not realized because one of the customers who was expected to participate, in the end refused to participate due to necessary installations of the prototype converter. Therefore, only a single heat pump was tested in TREFOR's supply area.

TREFOR's demo site is located close to the city of Vamdrup, a rural area with 18 customers on one LV feeder, see the aerial photo in Figure 14,. Four of the customers are electrically heated, including the chosen customer with the heat pump. The 10/0,4 kV transformer has a capacity of 100 kVA. The short circuit level is low due to the transformer size and therefor interesting for this project.

Compared to the low voltage network on Bornholm, TreFor's network was much smaller, though the voltage unbalance was significantly larger. PQ meters were installed at the 10/0.4 kV transformer station, and two street cabinets after the demonstration household, shown schematically in Figure 15.

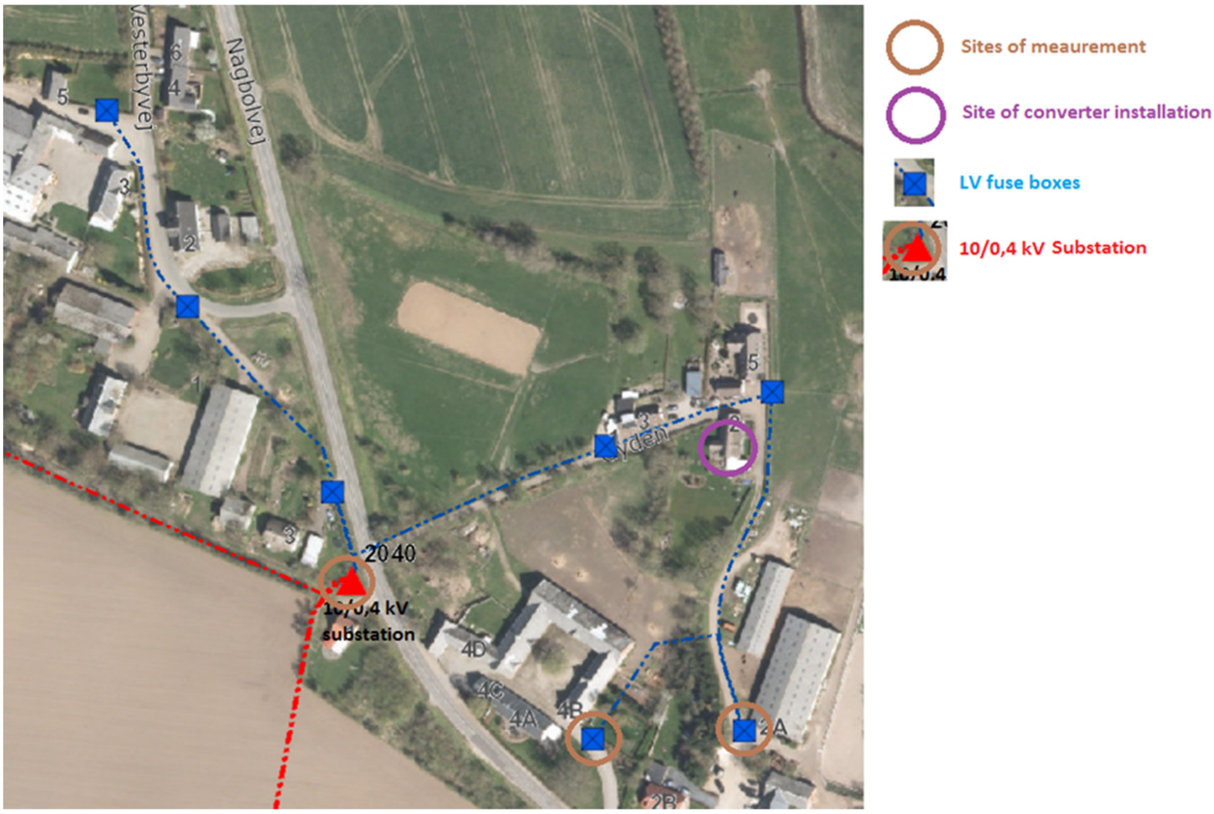


Figure 14. Aerial view of TREFOR demonstration site, with site of converter and sites of measurements shown.

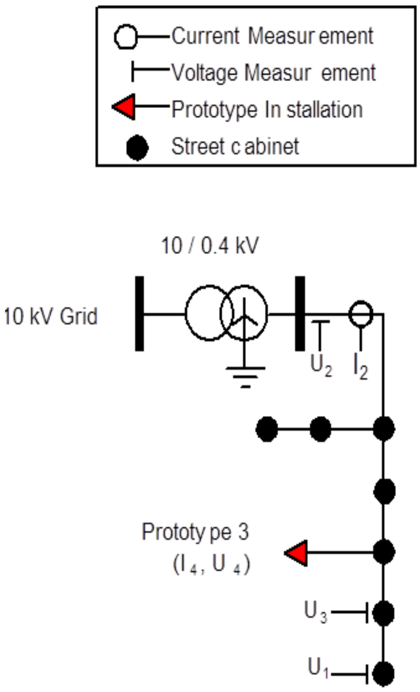


Figure 15. Schematic layout of test site in Trefors area.

7.3 Installation at customers

The customers all had heat pumps which were 100 % supplied with energy from the prototype converter, see Figure 16. On Bornholm, both homes had a PQ meter at the nearest street cabinet; this was also the intended setup for TreFor's demonstration, but by mistake the PQ meter was placed at an adjacent street cabinet. The voltage measured in the street cabinet differed slightly from the voltage measured at the prototype because of the impedance of the service line connecting the house to the street cabinet.

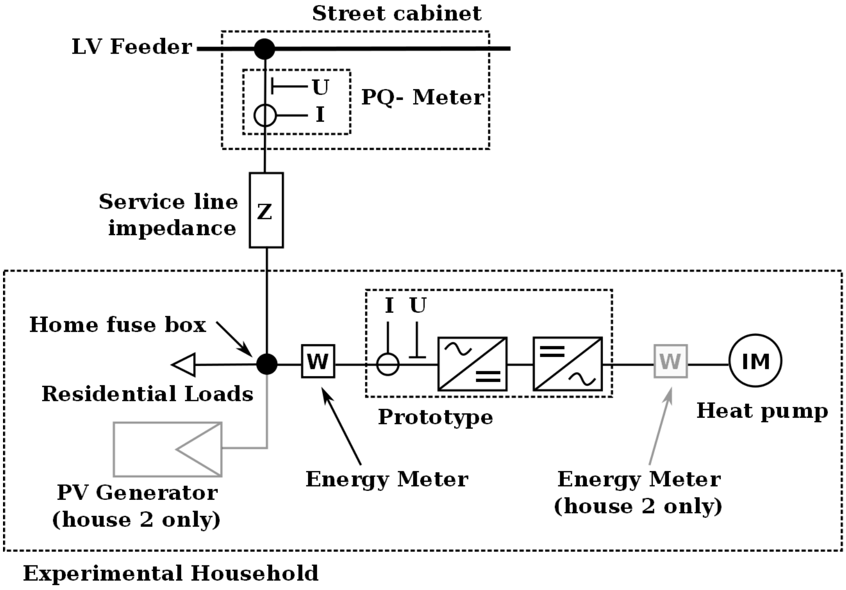


Figure 16. One-Line schematic diagram of prototype installation. PQ-meters were only present on Bornholm.

Initially, it was assumed that the heat pump side of the converter would be identical in all demo sites. This turned out to be optimistic, and in reality, each demo site had a rather different heat pump side, despite the superficial similarity of supplying 50 Hz, 230 V 3-phase power.

One of the heat pumps was rather large with a rating of 5 kWe, and when this device started, the inrush current triggered overcurrent protection of the prototype. Therefore, a soft starter was implemented in the converter to gradually increase voltage and current during the transition from Off to On.

Another heat pump had a single phase grid connection. Finally, the third heat pump required a neutral connection, which was not part of the original prototype design. A neutral wire was improvised by connecting it to the midpoint between the 2 capacitors of the DC-link, but this creative intervention may have damaged the prototype, see section 8.3.

7.4 Lessons Learned

Finding suitable demonstration sites was a challenge, and this section summarizes the lessons we drew from this experience. The key barriers to finding demonstration sites were the low number of customers with heat pumps, and the low number of LV feeders with significant voltage unbalance. Very few candidate sites, with both heat pumps, and weak LV networks were identified. The prototype entered into the customers' private domain, and the project had to address technical constraints, such as noise from cooling fans, and non-technical constraints, such an insurance liability. We had to respect that space heating is a critical service, and customers were skeptical of our assurances that their homes would always be heated. Therefore a contingency plan, in case of technical failure of the prototypes, was created, and communicated to the customers.

8 Lab and Field Demonstration results

8.1 Lab test results

The proposed converter concept and control was implemented and preliminary tested in the laboratory. Before deploying the hardware in the field it is important to know how the converter hardware and control behaves under certain conditions, thus the test setup from Figure 17 was realized. The voltage source and the line impedance were emulated using an AC programmable source (Chroma 16511). The reference voltages were balanced and the test impedance was $Z_U = Z_V = Z_W = 0.5 + j0.0075\ \Omega$. The unbalanced load was using different phase to neutral resistive loads, namely: 40 Ω on phase U, 80 Ω on phase V and no load on phase W. The proportional and integral gains were set to 4 and respectively 40.

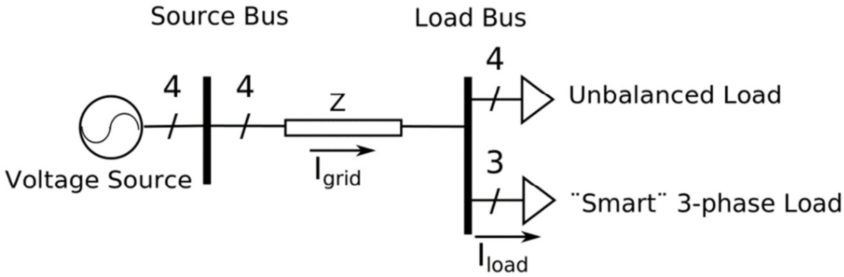
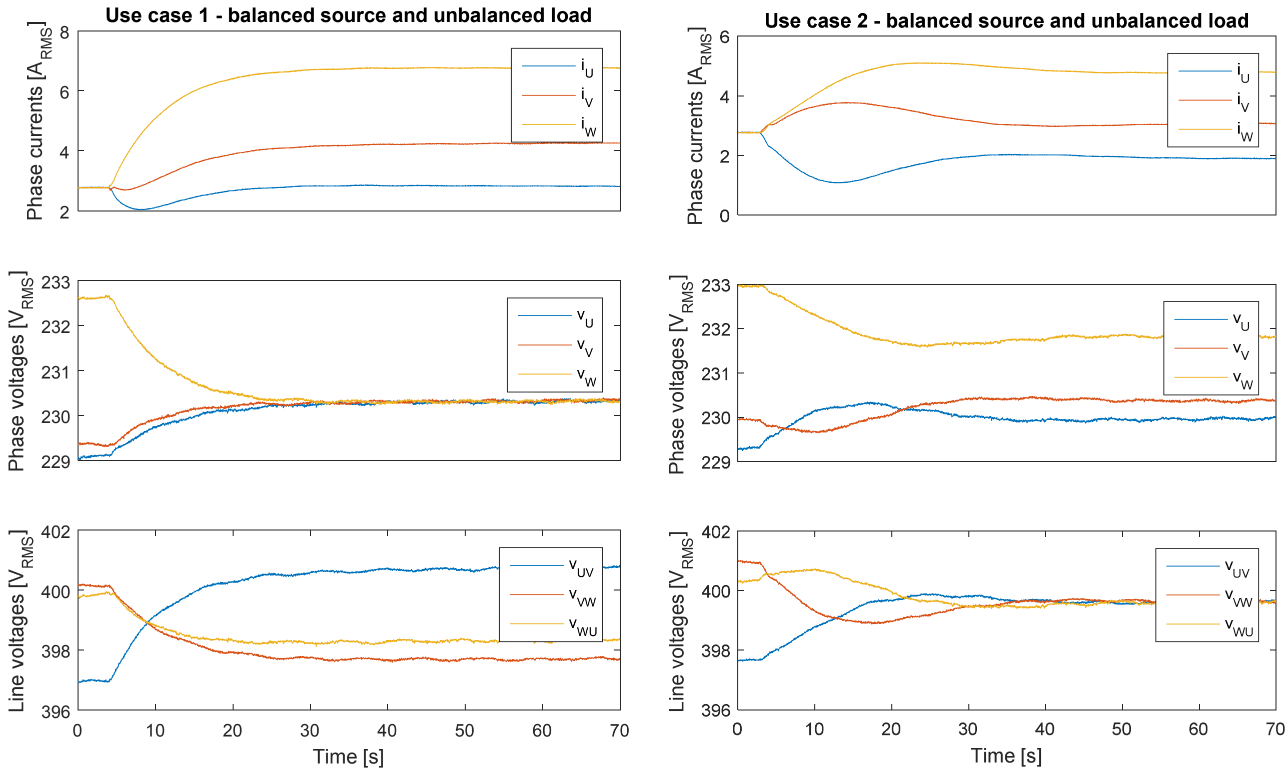


Figure 17. Two bus test system. The line has 4 conductors: 3-phases and neutral. The unbalanced load also has 4 conductors, while the smart load only has 3 phases, and no neutral connection.

The test results for the first two use cases are shown in Figure 18. For practical reasons, the other two use cases, using reactive current as control tool, could not be tested in the laboratory due to the way the grid emulator is controlled.
The converter is operating in the baseline use case 0 up to about $t = 4\ s$, time at which the controller is activated. Before the controller activation it can be noticed that the converter (the emulated heat pump) draws balanced currents and there is unbalance in both the phase and line voltages.



a) b)

Figure 18. Voltage control operation with balanced voltage source and unbalanced load: a) Use case 1. b) Use case 2.

Looking at use case 1 in Figure 18a, after the controller activation it can be seen that the currents are modified to no longer be equal and the converter starts to change the load currents in the direction of removing the phase to neutral voltage unbalance. The phase with the highest voltage (W) will be used to draw the highest power, and eventually the other two phases will draw very little power of will experience negative power flow. It can be seen that while the phase to neutral voltages get into balance (PVUR becomes null), the phase to phase voltages are changed to different values – however the level of line unbalance seems to be kept to a similar level.
The transient performance is shown also for use case 2 in Figure 18b. This time the phase to phase voltages are balanced (VUF becomes null), while the phase to neutral unbalanced being also reduced.

In [C], a direct comparison was made between simulation results, and lab test results. The comparison is shown in Figure 19. The controllers seem to behave as expected and are therefore deployed for field tests.

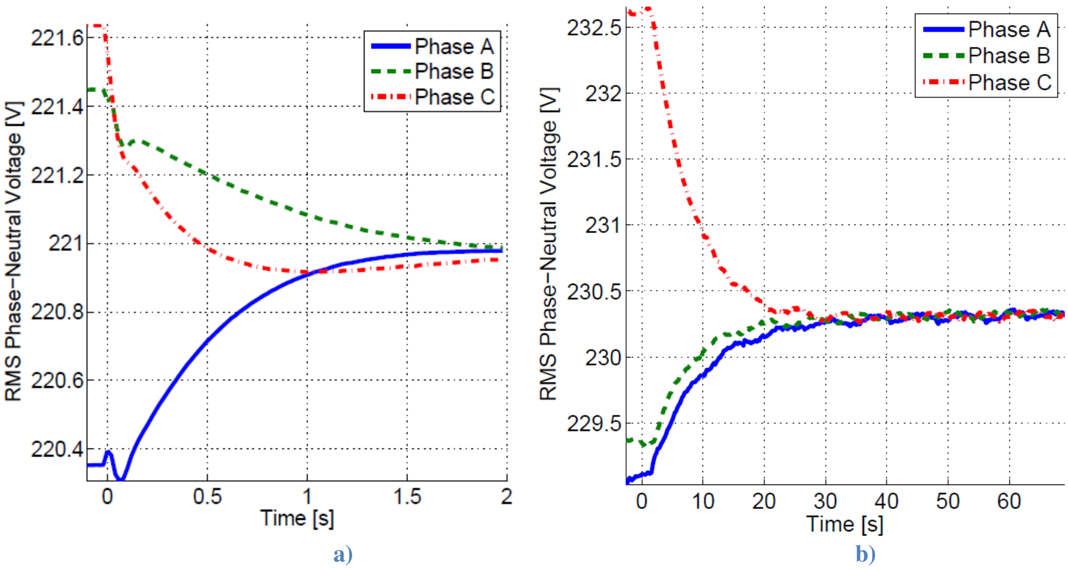


Figure 19. Simulation (a) and Lab test (b) of use case 1 showing the convergence of P-N voltage. The initial conditions are not identical, and the time scale differs, but the overall effect of the controller function in the simulations and prototypes is comparable.

8.2 Field results: Bornholm

These results are fully described in [E]. To summarize the conclusions:

The AFE rectifiers were evaluated in field tests while executing 4 alternative control algorithms. The field test results show that all the algorithms achieved their goal of reducing voltage unbalance, not just at the controllers own terminals, but throughout the distribution system. The performance of use case 1 (P-N balancing using active power) was best, see Figure 20 and Figure 21. In some cases, the reduction in voltage unbalance was larger at the nearest street cabinet than at the AFE's own terminals. Active power control (use cases 1 & 2) is clearly more effective at reducing voltage unbalance than reactive power control (use cases 3 & 4). The use cases optimized to reduce PVUR (use cases 1 & 3) achieved the largest reduction of PVUR, as expected. These two algorithms also significantly improved the VUF; in two locations UC 1 gave the largest improvement in VUF of any use case. The use cases optimized to reduce VUF (use cases 2 & 4) were effective at reducing VUF, but had a marginal effect on PVUR. These field test results contradict the results of earlier laboratory tests [C]. All of the voltage balancing algorithms increased the current unbalance (as measured by PCUR) in the service line connecting the prototypes to the street cabinets. However, the current unbalance at the substation was reduced in all use cases, with the largest reduction in use case 1. One of the prototypes was installed at a household with 2 single-phase PV inverters. Results show that this prototype was more effective at reducing the voltage unbalance when the PV was producing energy.

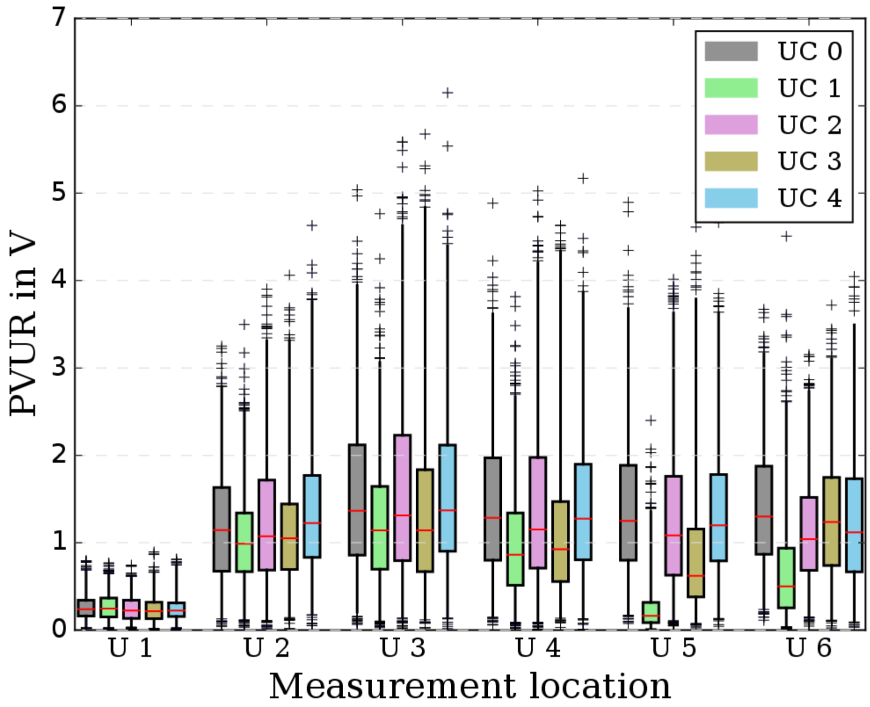


Figure 20. PVUR at all measurement points for all use cases. The Y-axis is the number of volts which the mean PN voltage differs from the most extreme voltage. The box shown the 2nd to 3rd quartile, the median in red the, whiskers show the 1. and 99. percentiles.

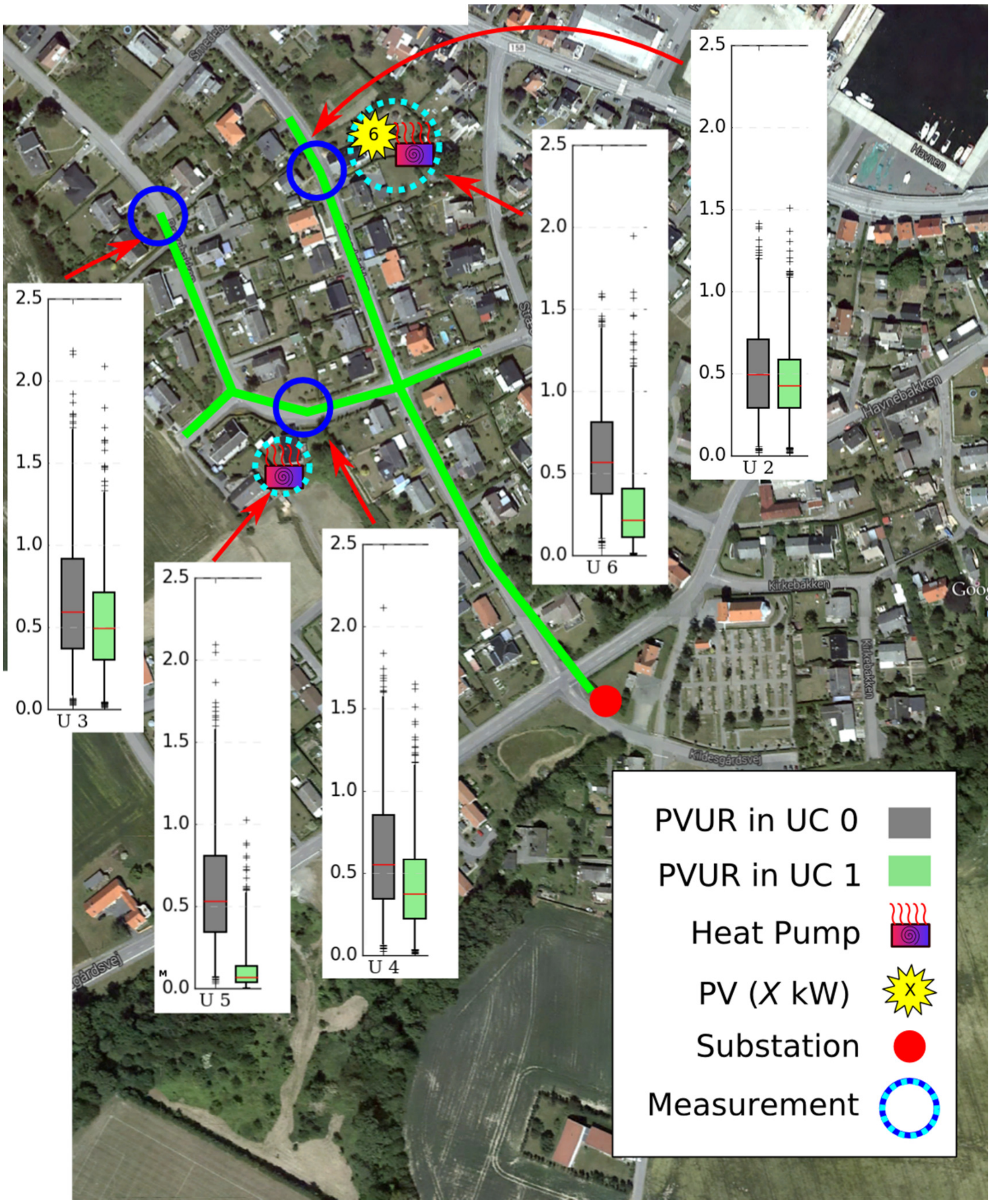


Figure 21. Comparison of the PVUR in use case 0 (BAU) and use case 1 at 5 measurement points. Photo credit: Google Maps.

8.2.1 Time Series Analysis during activation of Use Case 1

The demonstration switched between use cases at fixed intervals. The prototype at U5 switched once per day, the prototype at U6 switched twice per hour. Use Case 1 was executed immediately after Use Case 0 (the base case), and therefore, samples taken immediately before and after the use case transition were examined to see the effect of activating use case 1.

For prototype 1, there were only 8 transitions from use case 0 to use case 1. Data from 4 minutes before the transition, and 5 minutes after are shown in Figure 22.

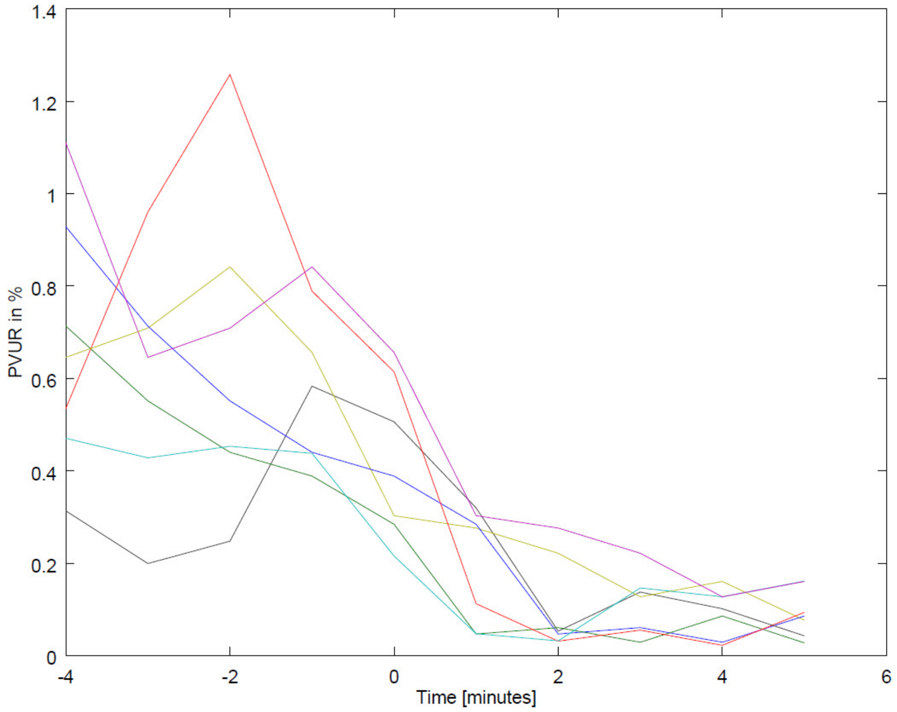


Figure 22. PVUR at U5 during transition from UC 0 to UC 1. The use case changes at time 0. Each event is shown in a different color.

For prototype 2, there was data from over 200 transitions. Therefore, the data was analyzed by taking the average PVUR at each minute before and after the transition, see Figure 23. The PVUR at the prototype itself, U6, decreased significantly, the other measurement points did not show significant change.

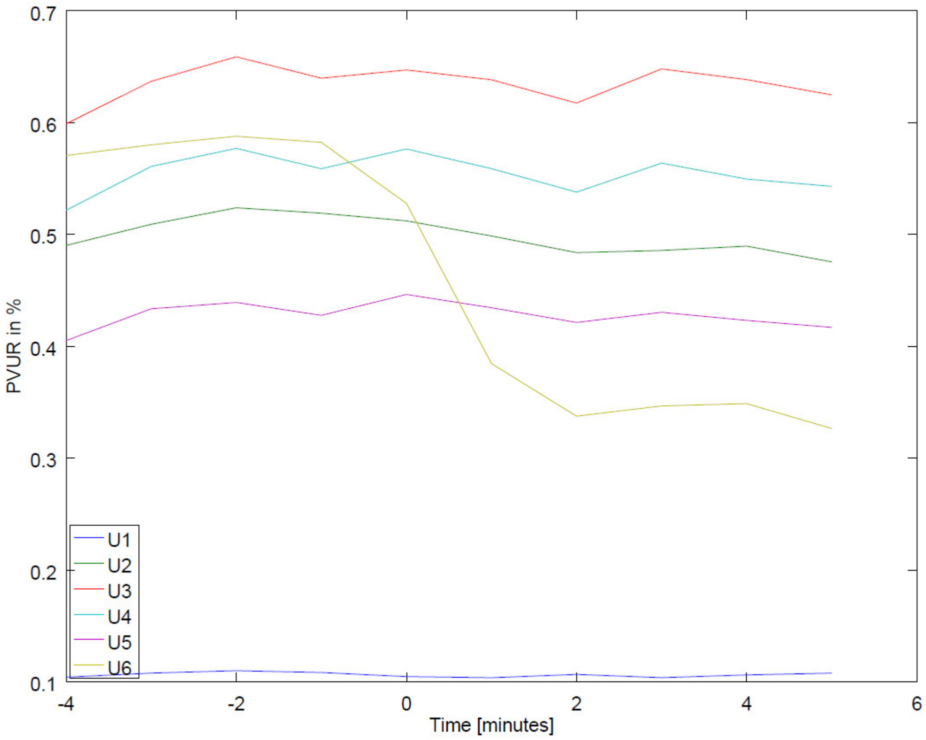


Figure 23. Average PVUR at all measurement points when prototype 2 (U6) transitions from UC0 to UC1.

8.3 Field results: TreFor

Analysis of the demonstration results from TreFor revealed an unwelcome development: the use cases all *increased* phase unbalance at all points in the network, except at the prototypes own terminals. This was of course, very concerning, and a full explanation was needed.

After the field test, the prototype was dismounted and shipped back to AAU's laboratory, to undergo post-mortem testing. This test revealed that the voltage sensors of the unit were mis-calibrated. Feeding the device power from a balanced laboratory power supply produced measurements unbalanced by +/- 2 V. This explains why the unbalance reported by the device was reduced, while the unbalance measured in the network increased. It is unclear what caused the voltage measurements to become corrupted, but it was observed that the 2 serially connected DC-link capacitors had widely differing voltage (120 V difference). This prototype was different from the others in that it had a neutral connection between the heat pump, and the mid-point of the DC-link capacitors. We suspect the faulty voltage measurements are related to this hardware configuration. Nevertheless, the data from TreFor was analyzed, and described in the remainder of this section.

The analysis of field results starts by examining the box-and-whisker chart of the PVUR, shown in Figure 24. As mentioned previously, the prototype itself (U4) showed a greatly reduced PVUR in use cases 1 and 2, compared to the base case (use case 0). This validates the feedback method at the heart of the balancing algorithms, and well-calibrated measurements at the neighboring street cabinets (U1 and U3) did indeed show that prototype operation had a significant impact on voltage unbalance. Unfortunately, that impact was the opposite of the intended, with median PVUR rising by about 35 % in use case 1, and 50 % in use case 2. Also at the 10/0.4 kV transformer (U2), unbalance was increased by 19 % and 31 % in use case 1 and use case 2 respectively. Using reactive power to balance voltage (use cases 3 and 4), did not have as large a negative effect as using active power.

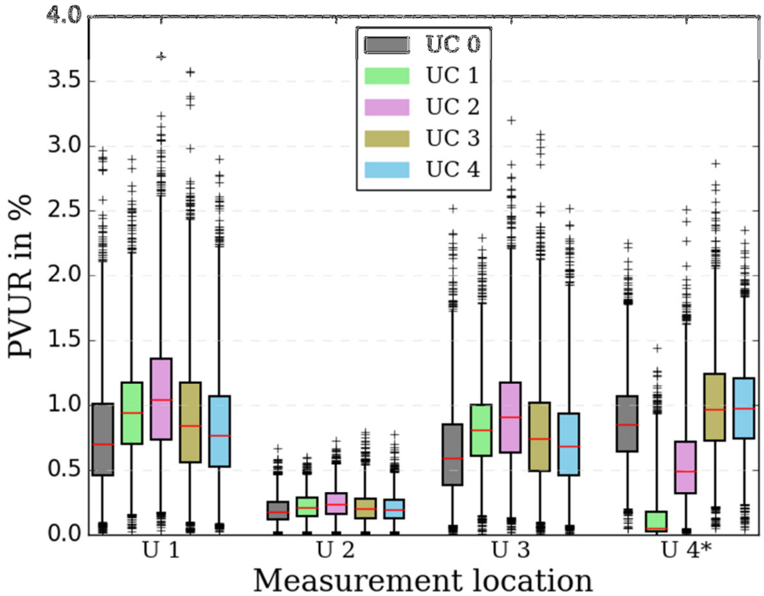


Figure 24. PVUR at all measurement points for all use cases (abbreviated UC) at TreFor demonstration site shown in a box-and-whisker chart. The box spans between the 2nd and 3rd quartiles, and the red line is the data set median. The whiskers extend to the 1st and 99th percentiles, and plusses denote outliers. The (*) at U4 is to highlight that these mearements are miscalibrated.

Regarding voltage unbalance measured by VUF, shown in Figure 25, the performance is scarcely better. The increase in VUF caused by the prototype operating with miscalibrated sensors was less than the increase in PVUR. Even with the prototype's own faulty voltage sensors, the VUF was barely reduced.

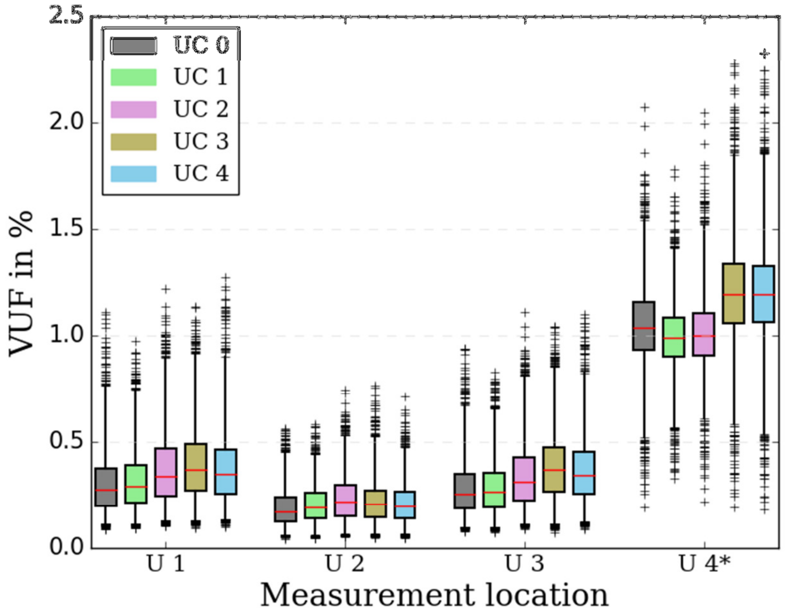


Figure 25. VUF at all measurement points for all use cases at TreFor demonstration site. Miscalibrated measurements are shown for U4.

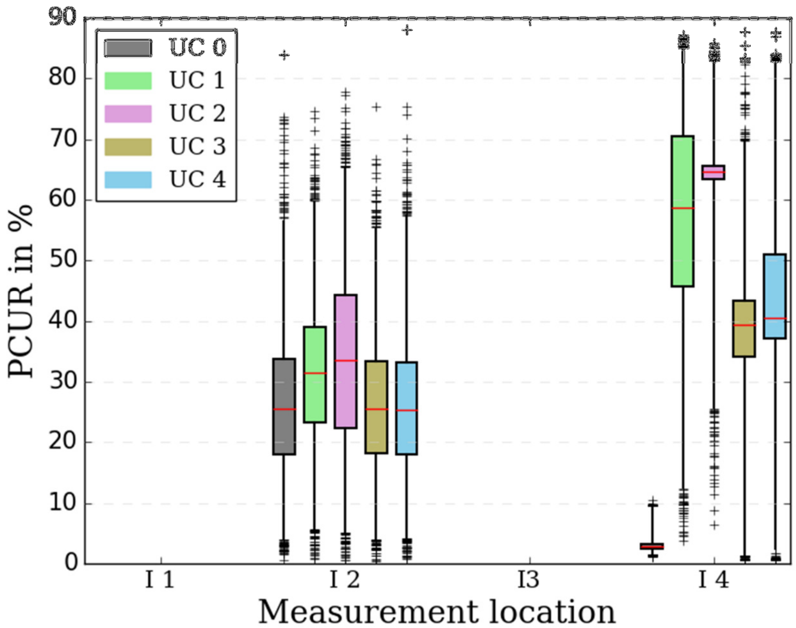


Figure 26. PCUR at all measurement points for all use cases at TreFor demonstration site. No current measurements were taken at measurement locations 1 nor 3.

The current unbalance at the substation (I2), increased along with the voltage unbalance in use cases 1 and 2, as shown in Figure 26. The data showed that despite the faulty voltage sensors, the prototype did draw mostly balanced current in the base case.

Considering the hardware error, these numerical results are mostly in line with what was expected after analyzing data from the other demonstration site. One deviation from expectations is in use case 1. On Bornholm, one of the prototypes almost eliminated PVUR at its terminals, but in doing so increased the VUF. In the case of the TreFor prototype, the PVUR was drastically reduced at the prototype without increasing VUF. Another difference was seen in use case 2, where the TreFor prototype somewhat reduced the VUF, but reduced the PVUR by around half. On Bornholm, the prototypes had a smaller reduction of PVUR in use case 2.

9 Summary of technical findings

Voltage unbalance can be calculated in (at least) 2 different ways, the most appropriate figure of merit depends on priorities of the system operator. The 'true definition' of voltage unbalance, also called the Voltage Unbalance Factor (VUF), is widely used in transmission system analysis. In 4-wire low voltage distribution systems, the Phase Voltage Unbalance Factor (PVUF) better captures the phase-neutral voltage constraints most pressing for Danish DSOs. Alternative voltage balancing algorithms were evaluated using both figures of merit. The alternative algorithms are summarized in table below:

Summary of alternative balancing algorithms.

Output \ Feedback Signal	**Phase-Neutral RMS U**	**Phase-Phase RMS U**
Unbalanced Active Current	Use Case 1	Use Case 2
Unbalanced Reactive Current	Use Case 3	Use Case 3

The results from the simulations and lab tests agreed with each other [C, H], but these results were not always consistent in their details with the field tests [E]. This is discrepancy is explained by saturation of the controllers, irregular active power consumption of the heat pumps, and the dynamic nature the operating power system. What can be concluded with confidence is that all algorithms reduced voltage unbalance, at the prototypes themselves, and in the feeder as a whole. The voltage balancing was achieved by increasing the current unbalance at the prototypes themselves, but at the substation, aggregate current unbalance was reduced.

The algorithms using unbalanced active power (use cases 1 & 2) were more effective than those using reactive power (use cases 3 & 4). This is because LV networks are primarily resistive, and active power has a much greater influence on voltage variation.

Regarding the algorithms effect on VUF, simulations predicted that use case 1 would have little effect on this figure of merit, while use case 2 was expected to greatly reduce VUF. The field demonstration found that neither of the algorithms greatly reduced VUF, and use case 2 was only slightly better at reducing VUF than use case 1.

In use case 1, PVUR was reduced by 87 % at one prototype in the field test, and 62 % in another, similar to what was predicted by simulations. Simulations showed that use case 2 roughly halved PVUR, but the field demonstration showed a much smaller decline (usually < 10 %).

The simulation and lab tests had steady-state unbalance, but the unbalance in the operating power system of the field trial was constantly changing. This creates a risk when the unbalance changes, the controller may be too slow to follow, and in fact may worsen the situation compared to BAU. Looking at the upper extreme values of unbalance, they generally follow the median values of unbalance – when median values are reduced, the extreme values are reduced, and when median values increase, extreme values increase. Therefore, we do not find any evidence that the controller is too slow to react to the changing nature of unbalance. Note that no fault conditions were observed during the field trial.

An interesting observation was made when comparing the voltage unbalance measured at the prototypes themselves, to the unbalance measured at the nearest street cabinet. In some cases, the relative decline in PVUR and VUF was larger at the street cabinet then it was at the prototype itself.

This provides evidence that the voltage balancing service delivered by the smart appliances is more valuable to the network, than it is to the private household.

Two of the three prototypes were installed on the same feeder, and different use cases were active in each prototype, in all 25 different combination of use cases were tested (all permutations of 4 balancing algorithms, plus 1 base case running on two prototypes). The interaction of the two prototypes was measurable, and the results were well predicted by the sum of the effect of each prototype operating in isolation.

In general, periods of high PV production correlated with higher voltage unbalance because of the proliferation of single-phase PV inverters [E]. One of the prototypes was installed in a household with 2 different single-phase inverters. For this prototype, the effect of the voltage balancing algorithms was relatively larger when there was high PV production, thereby mitigating the unbalance caused by the home's own unbalanced PV.

In addition to the 4 use cases demonstrated in the field, a 5th control algorithm, based on a *dq* decomposition of voltage was developed and tested in the lab [F]. This controller was generalized to illustrate the tradeoffs between balancing grid voltage, balancing converter current, and maintaining a constant DC-link voltage. Using the *dq* control to improve voltage unbalance resulted in fluctuations in the DC-link, and prioritizing a stabile DC-link lead to unbalanced converter currents.

10 Discussion – what is the impact on grid costs?

The simulation and demonstration results of the project have shown that there is an observable reduction in grid unbalance by active-front end rectifiers used in combination with heat pumps.

What is the value of improved phase balancing to grid operators?

The share of 0,4 kV feeders that need reinforcements in an unbalanced grid compared to a balanced grid is illustrated in Figure 27:

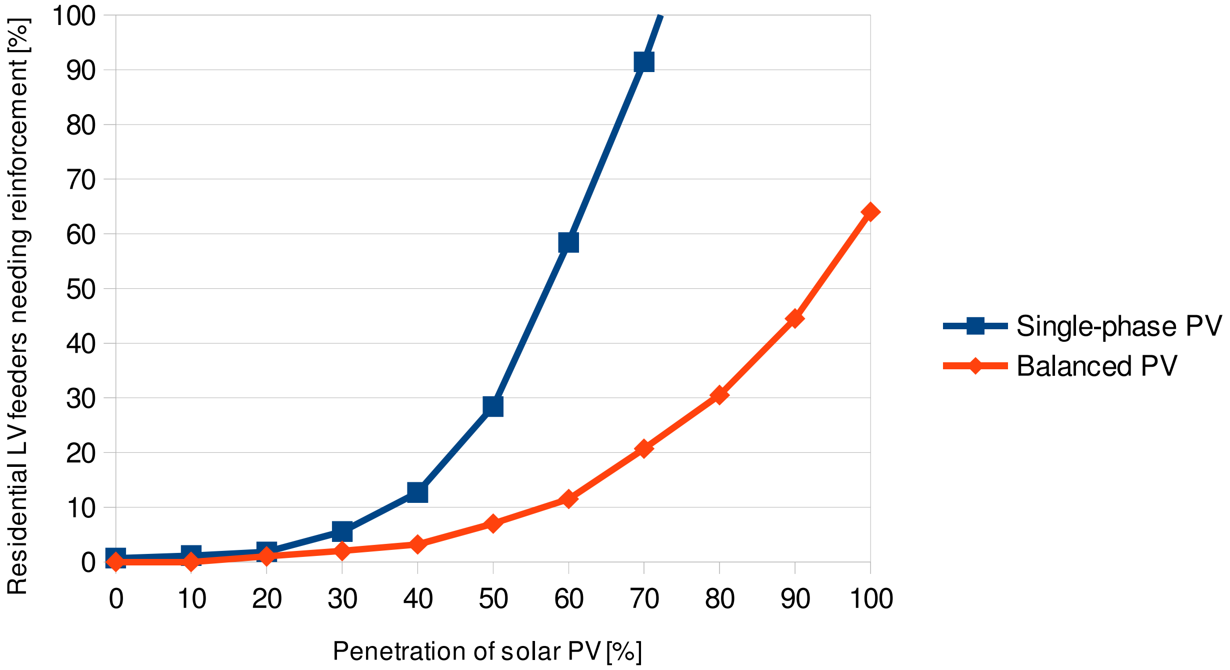


Figure 27. Illustration of the share of residential (defined as having more than 5 private homes) 0,4 kV radials that require reinforcement with different level of PV penetration. The share of feeders needing upgrade (y-axis) is shown for both an unbalanced grid (blue squares) and a balanced grid (red diamonds) as a function of PV penetration (x-axis). [14] and [1]

The figure shows that at same amount of PV penetration the 0,4 kV reinforcement requirement is larger in an unbalanced grid (blue squares) compared to a balanced grid (red diamonds). According to the figure, with 60% PV penetration, the required reinforcement due to voltage variation is approximately 10% of radials with more than 5 houses in a balanced grid, compared to above 60 % in an unbalanced grid.

At a high penetration level of single-phase applications (PV or heat pumps) the difference in share of reinforcements due to voltage problems between a balanced and unbalanced grid is significant and therefore has a significant economic impact for grid operators.

However, it is also important to bear in mind that at low penetration levels (which is the case today) there is no general need to reinforce the distribution grid and therefore no economic incentive to invest in equipment.

How much voltage unbalance compensation can active front end heat pumps provide?

The maximum grid balancing potential from the installed active front end heat pump was not possible to determine based on the measurements (e.g. Figure 22). The unbalance in the grid was not high enough to reveal the maximum compensation from the approximately 5 kW heat pump.

Further, the yearly variation in compensation potential from the heat pump was not determined due to operation only during five weeks in winter. The influence of high PV production was not investigated for the same reason, which means it is not possible to conclude how much compensation heat pumps can provide during the summer when PV production and voltage increase problems is highest.

Due to the limited knowledge of how much the active front end can compensate phase unbalances in different grids and grid loads it is not possible at this stage of research to do reliable calculations on the cost saving potential for DSOs. Additional simulations and demonstrations are needed to identify the correlation between required activation of compensation at different location the distribution grid to achieve the required unbalance compensation to avoid voltage problems.

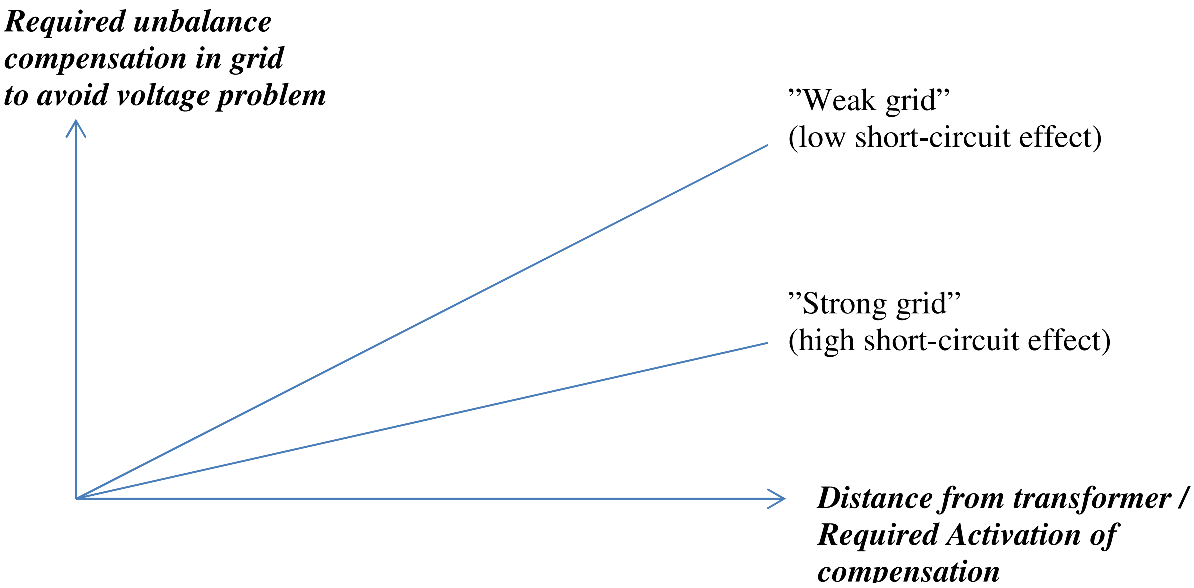


Figure 28. Illustration of required activation to achieve required unbalance compensation – further work is needed to determine scale and curves for different grids

It could be a good approach for further work to test the required compensation effect, possible compensation from active front end heat pumps and the economic value in worst case conditions, i.e. radials with beginning voltage and unbalance problems.

In general it is necessary to understand how unbalance compensation at customers (heat pump, PV, etc. with active rectifiers) compares to other voltage quality solutions. Further, to understand how many installations are needed to solve different kind of grid problems.

Is grid balancing with active-front end heat pumps a cost-effective solution?
As mentioned in the introduction (section 3.1) grid operators have different options to mitigate problems with unbalances in distribution grids. If active-front end heat pumps are to provide grid balancing it is necessary that VFD heat pumps, not on/off heat pumps, are installed at customers – further it is required that customers/manufacturers choose an active rectifier instead of a simple rectifier. The type of heat pumps and impact on distribution grid is illustrated below:

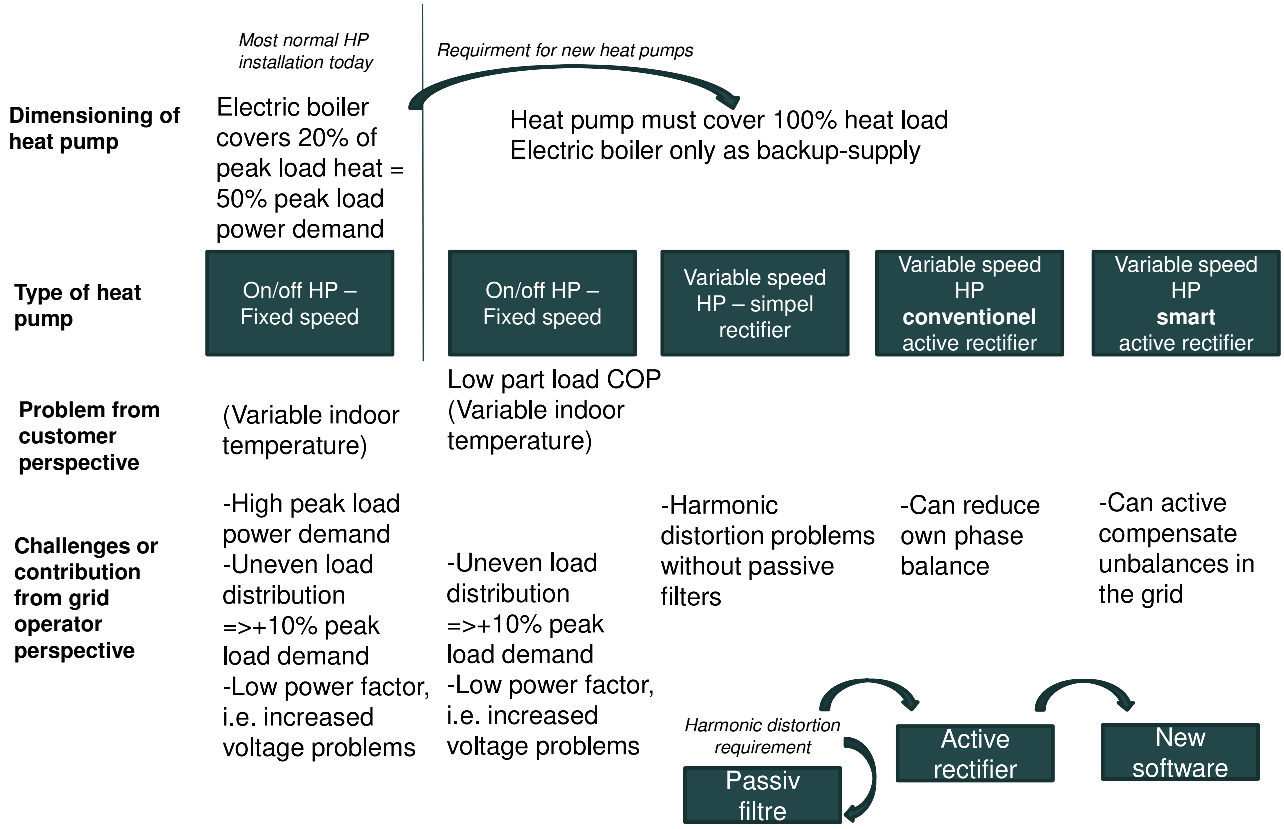


Figure 29. **The development in type of heat pump and the implications from the grid operator perspective.**

<u>Positive effect of VFD heat pumps</u>

- The simulation results in Figure 11 shows that VFD heat pump improves the power factor (voltage variation) compared to the induction motors used in on/off HPs.
- The COP (power-to-heat efficiency) is higher for VFD heat pump compared to on/off HP which is the main economic incentive to invest in the technology.
- More part-load operation can increase the incentive to choose VFD heat pump.

Possible problems with balancing from VFD heat pump

- It is necessary to invest in an active rectifier compared to simple rectifier (passive filter) – decreasing costs of active rectifiers, especially IGBT switches, can make it attractive to choose this technology in the future. Initial cost estimations indicate that an active rectifier currently is a high additional cost to a residential heat pump.

- A heat pump with active front end is not possible to provide additional unbalance compensation to the grid when it operates at full load (maximum heat production) – this means that heat pump cannot contribute to grid unbalances in this situation unless excess capacity is installed in the rectifier, which obviously increases the cost to the consumer.

- To be able to provide grid balancing, additional electricity consumption (e.g. idling losses) of the active front end rectifier provides additional economic costs that customers should be reimbursed for.

The alternative cost of providing balancing by other solutions (active filters other places in the grid or other appliances or new transformer) sets an upper limit for the cost of providing the balancing from heat pumps.

11 Recommendation for further work

The field demonstration results proved that a small number of heat pump loads, when intelligently controlled, can improve voltage unbalance in a low voltage distribution system. However, testing only 3 devices, one of which was faulty, gave only a limited amount of raw data to support broader adoption of the algorithms developed in this project. All three of the demonstrated prototypes gave different results, and these results deviated in some ways from laboratory tests and system simulations. Without complete control of all variables in the field, it is infeasible to analytically explain all of the field results. The following issues arose during the project, which point towards future work clarifying how 3-phase power electronic loads can participate in voltage balancing:

- On Bornholm in use case 1, prototype 1 managed to reduce PVUR by 87 %, while prototype 2 only reduced PVUR by 62 %. This difference remains unexplained.

- Simulations and lab results show that use case 2 can completely remove VUF, but in the field demonstration, use case 2 only reduced VUF by 20 %. It is not clear why the field results differ so much from the simulations.

- The field demonstration site on Bornholm did not experience large voltage unbalance. In general, testing at more demonstration sites would prove that the algorithms are generally applicable, regardless of network conditions.

- Behavior of the algorithms during faults has not been examined in this project, but would be an important consideration before practical deployment of the algorithms.

- The *dq*-algorithm described in section 4.4.1 was only tested in the laboratory; it was not mature enough to try out during the demonstration. This algorithm has potential to improve VUF, and is similar to other algorithms found in the academic literature. Real trials with this class of algorithm would allow a complete comparison of all alternative methods for controlling current to compensate for voltage unbalance.

- Compensation of zero sequence voltage could be performed by implementing a 4-wire converter that had complete control of the neutral current. Developing algorithms for such a device were outside the scope of this project.

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A.

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Appendix

A. Technical concept

The proposed technical concept is shown in Figure 30, where the power delivered to the heat pump is processed by the AC/AC converter (back to back). The motor side converter part controls the end user temperature via the speed control of the induction motor and the rest of the components integrated in the heat pump. The grid side converter delivers the necessary power to the motor side converter via the DC-link while controlling the grid currents to be sinusoidal with a low percentage of harmonic content. Since the grid side has control over the grid currents, grid support can be implemented as well. Controlling the magnitude and phase of the grid currents the grid can receive support in the form of reactive power, unbalance compensation or even harmonic compensation.

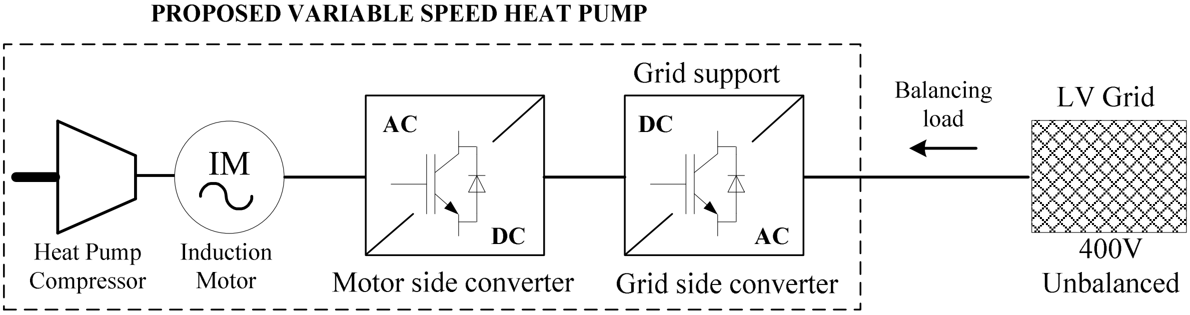

Figure 30. Proposed variable speed heat pump with grid conditioning functions

1. Hardware of the back to back converter

Silicon Carbide (SiC) devices exhibit superior performances compared with Silicon (Si) devices and they have become widely available on the market in different packages. It is advantageous to build a SiC heat pump converter if either efficiency or power density is desired. Figure 31 presents the SiC heat pump back to back converter.

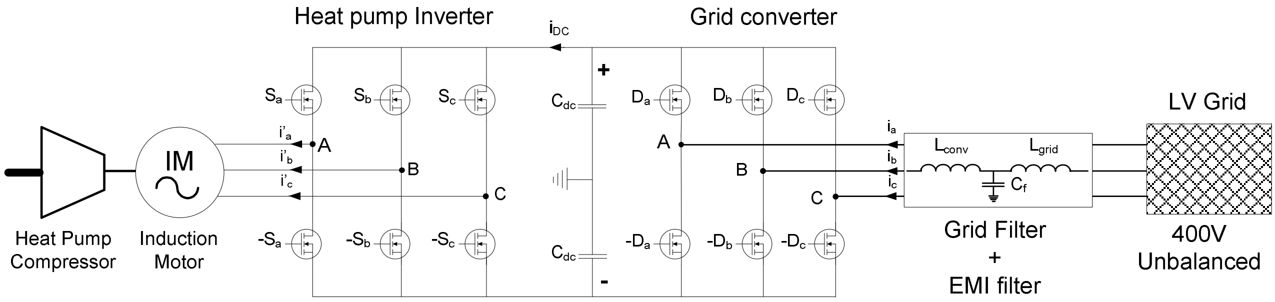

Figure 31. Proposed variable speed heat pump with SiC back to back converter

Transistors in this topology can switch at significantly higher speed compared with traditional Si converters, enabling the operation at high frequency. The high frequency operation can be utilized firstly to reduce the necessary filtering on the converters AC interface. It can however also make room for utilization of new control strategies which take advantage of the high sampling and control frequency.

An example of a prototype built for this project is shown in Figure 32. The building block is a DC/AC converter built symmetrical with respect to the DC-link connections to be able to parallel connect them on the DC-side.

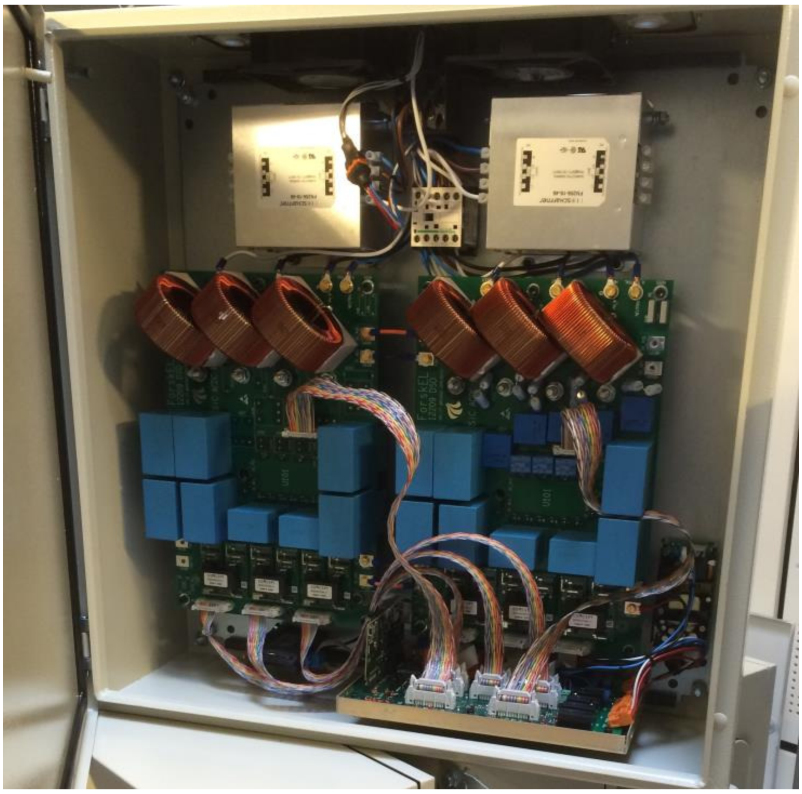

Figure 32. Back to back converter prototype

The block schematic of the converter is shown in Figure 33. Two DC/AC converters are parallel on the DC side, two EMI filters are placed in the input and output of the AC/AC converter to be able to comply with the EMI standards. LCL filters are integrated in each DC/AC converter PCB. A relay is used to disconnect the converter from the grid at startup or in case of faults. A digital signal processing (DSP) based control board is in charge of sensing and commanding all the units, including a GPRS communication for data transfer.

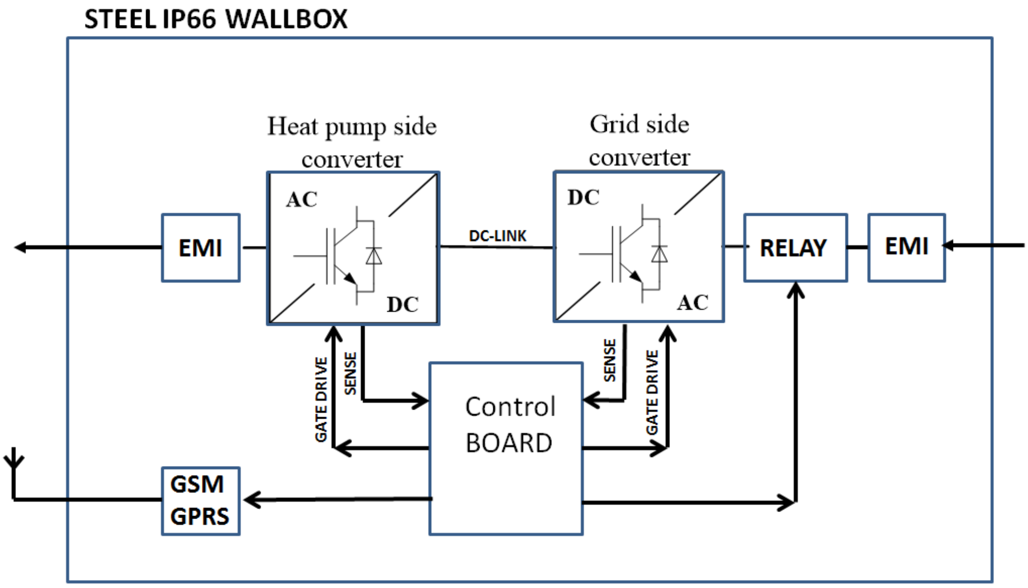

Figure 33. Back to back converter prototype – block schematic

1. Control strategies

The focus is placed on the control of the grid side converter, as it is the key component that can enhance the integration of more heat pumps into the distribution grids.
The first control strategy developed was based on the classical *dq* control widely used in grid and motor controllers in industry. The simplified control block diagram is shown in Figure 34.

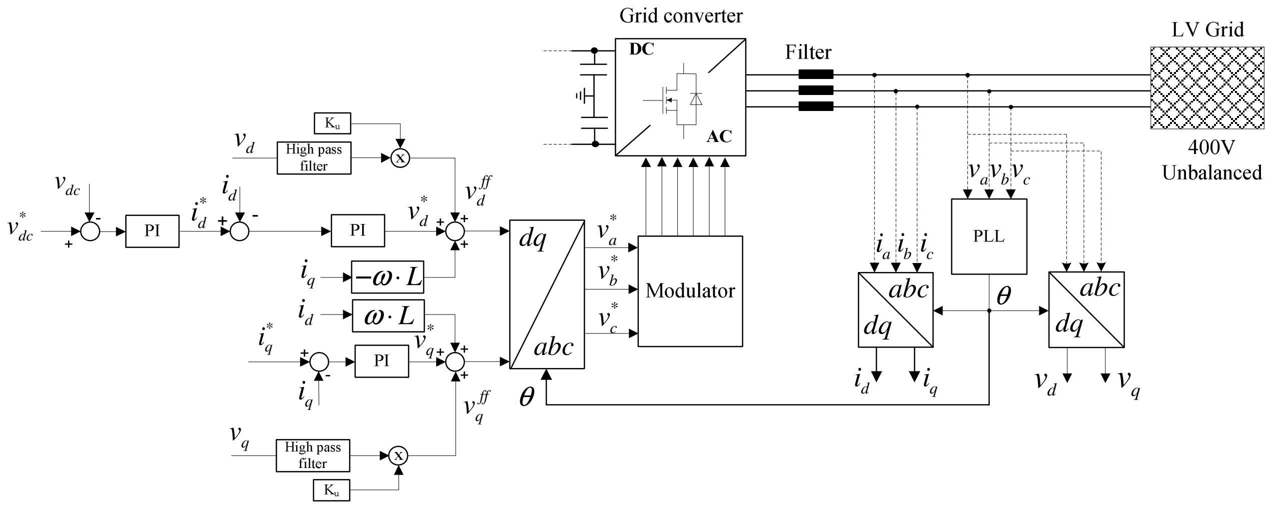

Figure 34. Rotating *dq* frame control with AC component feed-forward

When controlling the currents using PI error compensation, the grid voltages and currents are rotated with the phase locked loop (PLL) estimated grid angle in the positive sequence direction. Due to the unbalance, second harmonic oscillations are present on the rotated *dq* grid voltages. The oscillations are extracted and an unbalance factor *K* is used to feed-forward an unbalanced reference that will oppose the negative sequence direction of the grid voltages. These oscillations can be used to provide support for the grid voltage unbalance, as introduced in [15]. When the *dq* frame control with AC component feed-forward is used, the design of the PI current controllers must be realized with a high bandwidth - SiC transistors make that possible. Negative sequence current is drawn from the grid as such that from the grid phase voltage with the lowest magnitude the smallest current is drawn [15]. Furthermore, the way the feedforward signal is generated and used can lead to further applications [16].

A similar strategy is proposed in Figure 35, with control achieved independently on each phase. Instead of rotating the grid voltages and currents with the grid phase angle, more effort is allocated to integration of the sinusoidal signals using the proportional resonant (PR) controller.

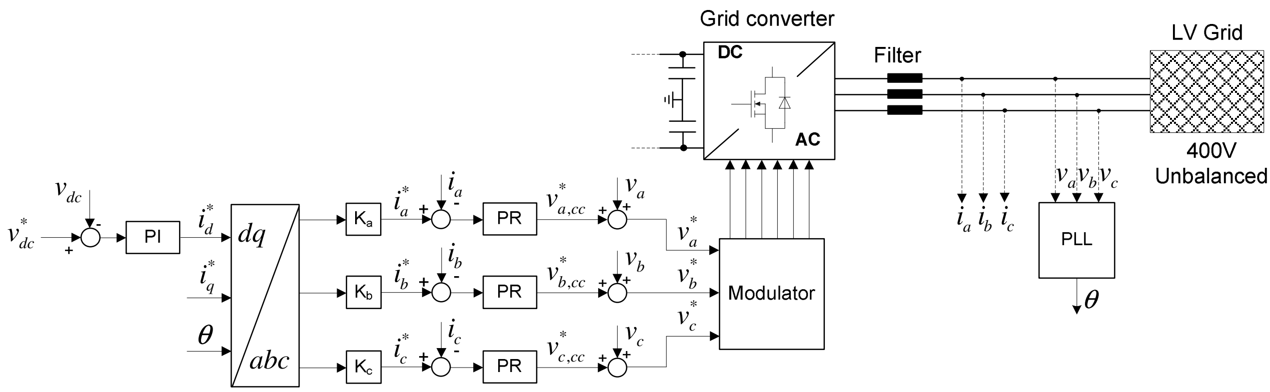

Figure 35. Stationary *abc* frame control with independent phase loading factors

A PI controller is still employed to control the magnitude of the DC-link voltage, setting the needed active current reference. A phase locked loop algorithm suitable to operate correctly under unbalanced grid voltage is required for both strategies [17]. The estimated phase angle is used to rotate in stationary frame the *dq* current references. Basic current references are then available for the current controllers. Since the measurement and control is realized on each phase, it is possible to adjust the current references independently for each phase. The grid and filter impedance will always impose limitations on what are the limits of the three references. In the three-phase three-wire structure as considered in Figure 35, neglecting high frequency common mode currents, the sum of the three phase currents will always be zero.

The adjustment factors can be introduced to adjust the current sharing between the three-phases, namely: *Ka* , *Kb* , *Kc* . A local droop controller can be employed to adjust the current sharing factors, when no communication with a DSO controller is available. In case there is a communication line with a DSO controller, the contribution to the total consumed heat pump power for each phase is to be adjusted to best fit the current situation of the grid. Reactive power can be demanded when the grid operates at a low power factor.

Example operation of the two control strategies is shown in Figure 36, where the grid voltage references were setup with the RMS values of the three-phases Vg,a = 230V, Vg,b = 234.6V, and Vg,c = 225.4V.

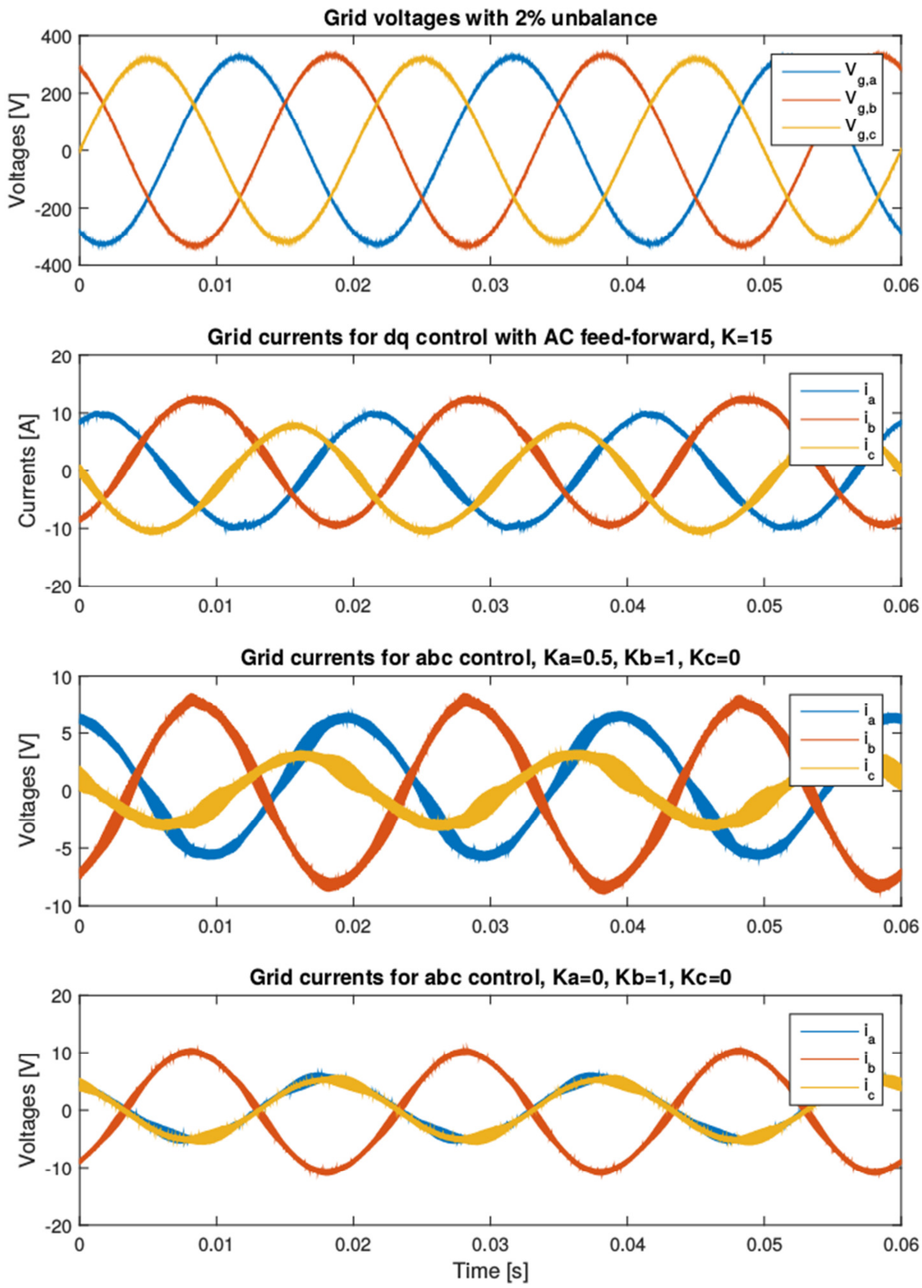

Figure 36. Experimental results: grid voltages with 2% unbalance; *dq* control with feedforward Ku =15; *abc* control (Ka = 0.5, Kb = 1, Kc = 0); abc control (Ka = 0, Kb = 1, Kc = 0)