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Abstract

This paper studies the impact of involving the demand side of the LV grid into the grid conditioning process. Heat pumps are distribution loads with a substation capacity increase in the last years, with expectancy of growth in the coming years. Controlling the loads is the first step in the transition to smart grids, and heat pumps are to be the first promising smart loads. They can be used for load shedding but also for unbalance compensation purposes. When they are equipped with a back to back compressor drive and a proper control strategy, grid support can be provided to reduce the negative sequence component in the voltage at the installation point. Two control strategies are proposed and investigated experimentally on a SiC heat pump converter prototype.

Introduction

The increased activity in the Low Voltage (LV) side of the grid increases the necessity for additional grid support. Household load profiles are changing, especially in residential areas, as new technologies are introduced. With regard to generation, the increase of photovoltaic systems installation has changed the traditional load curves of the distribution grid. With regard to loads, the number of heat pump installation is growing rapidly. For example in Denmark, because of the governmental ban of the oil and gas fired boilers as new heating installations, the electricity consumption of heat pump loads is expected to be more than double in next 10 years [1]. Due to this fact the peak demand power is also expected to be more than double. Therefore, the integration of large amount of heat pumps can be challenging unless they are controlled intelligently.

At present levels of penetration, heat pumps 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 1. 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 1.
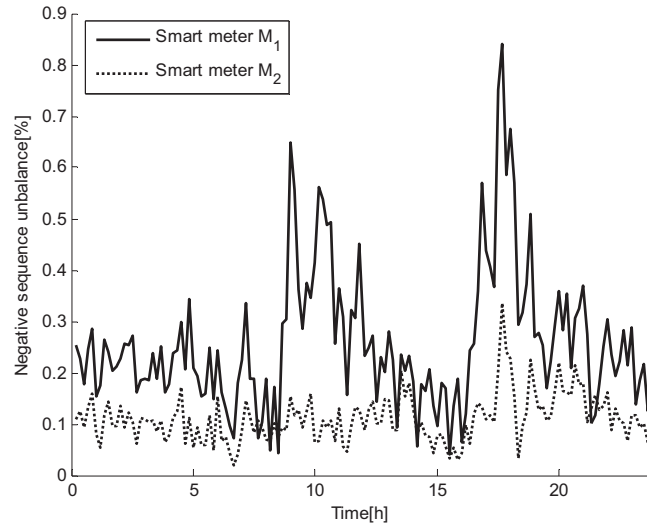

Figure 1: Negative sequence measurement in the LV grid in a winter day

State of the art heat pumps use the electricity and have low interaction with the grid. In case of abnormal grid operation are just required to disconnect. However, considering the changes in paradigm for which the entire grid suffers in its hierarchy and control, heat pumps must be equipped and prepared for grid support [2].

Recent development in Wide Bandgap Devices (WBD) such as Silicon Carbide (SiC) are seen as the next generation of switching devices for the power electronic converters used in many applications. With the continuing optimization of production and decreasing cost of the dies, SiC is expected to replace the conventional Insulated Gate Bipolar Transistors (IGBTs) which are approaching the theoretical limit of the silicon (Si) characteristics [3], [4]. The new generation of MOSFET SiC devices can operate in high temperature (above 200 °C) and high frequency (above 50 kHz) with low conduction loss, which can significantly increase the power density of converters.

For heat pumps, the specific interests of utilizing these devices are to improve the conversion efficiency or increase the power density, to develop novel control architectures and to maintain or decrease the over-all cost. This new concept of heat pump will have a variable speed drive which uses power electronics to adjust the speed of the compressor to match the heat demand. The power electrics of the variable speed heat pump will be controlled to compensate for asymmetrical loading of the 3-phases of the power distri-bution system. Improving the symmetry of the 3-phases will improve voltage quality for all customers in the network, and increase the number of heat pumps feasible to integrate into a given network. The new heat pump will also have advantages for the owner such as higher efficiency (COP), lower maintenance costs, and a more stable indoor temperature, though a disadvantage will likely be a higher investment cost due to the increased number of active devices.

In this paper, two different control strategies are investigated as possible candidates for unbalance grid voltage support. A SiC back to back heat pump converter prototype was realized to be used for experi-ments in a typical distribution grid with voltage unbalance. Control strategies are implemented and tested on the prototype to highlight the grid support possibilities using the grid side converter of the heat pump.

State of the art heat pumps

The state of the art heat pump topologies are shown in Figure 2 and 3. The simplest and the most common heat pump is the direct grid connection using an ON/OFF switch. 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 – a high startup current being drawn to magnetize the motor. Even worse, some are using single phase motors and are therefore connected to a single phase (230 V) creating unbalance in the distribution grid. An improved heat pump topology is shown in Figure 3, where a variable speed drive is used to drive the compressor. Using a power converter to control the motor results in a fine control of the temperature, and reduces the mechanical stress of the heat pump motor and compressor. The startup is soft which in turns helps the distribution grid and improves the reliability of the heat pump.
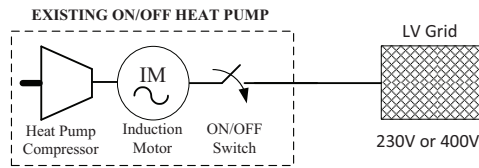

Figure 2: ON/OFF heat pump
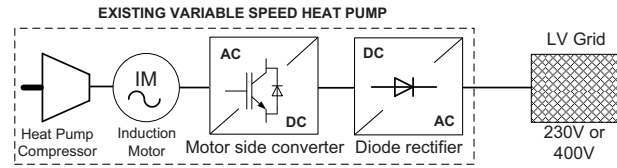
Figure 3: Variable speed heat pump

The topology from Figure 3 can also be implemented in single phase, disadvantageously introducing unbalance in the power grid. Some of these heat pumps can also help the grid by phase-shifting the load using the internal heat storage tank, if they can be controlled via a communication line by the distribution system operator (smart grid enabled).

Proposed heat pump with grid support

To address the challenges highlighted in the previous section, the smart variable frequency heat pump concept is proposed in Figure 4. The variable speed control of the motor that drives the heat pump compressor is achieved by a motor side converter. This control is state of the art 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.
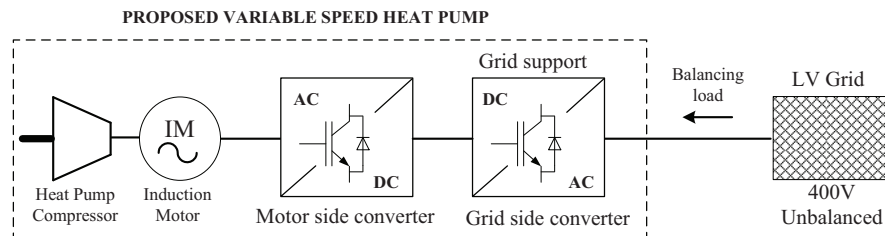
Figure 4: Variable speed heat pump with grid support

SiC devices exhibit superior performances compared with Si devices and they 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 5 presents the SiC heat pump back to back converter. Transistors in this topology can switch as 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 converter output. It can however also make room for utilization of new control strategies which take advantage of the high sampling and control frequency.

Figure 5: Variable speed heat pump with SiC converter

By having the control of the grid currents, the heat pump can draw sinusoidal currents at unity power factor and without or very low harmonics. Moreover, further services can be provided to the grid such as injection of reactive power, unbalance voltage compensation and eventually the low order harmonics introduced by other electronic devices can be compensated.

As it was presented in Figure 1, the grid voltage is unbalanced and drawing currents with different magnitudes from the different phases of the grid can reduce or ideally cancel the unbalance voltage in the coupling point of the proposed heat pump. 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 current references are not generated locally in the heat pump controller, but given by the DSO via a communication line.

Control strategies for unbalance voltage grid support

The focus of this paper is to provide the proper grid interoperability by means of unbalance voltage compensation. To deliver grid support functions this paper investigates two control strategies designed to reduce the negative sequence component of the grid voltage.

When the grid voltage is unbalanced, even drawing balanced currents with the grid converter will result in active and reactive power oscillations [5]. When controlling the currents using proportional integral (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. These oscillations can be used to provide support for the grid voltage unbalance, as introduced in [6]. Figure 6 presents the simplified block diagram for this strategy. The second harmonic components in the dq grid voltages are extracted, and an unbalance factor K_u is used to feed-forward an unbalanced reference that will oppose the negative sequence direction of the grid voltages.

Figure 6: Rotating dq frame control with AC component feed-forward

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 are making that possible when high frequency operation is achieved. 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 [6].

A similar strategy is proposed in Figure 7, 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. 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 [7]. 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 7, neglecting high frequency common mode currents, the sum of the three phase currents will always be zero.
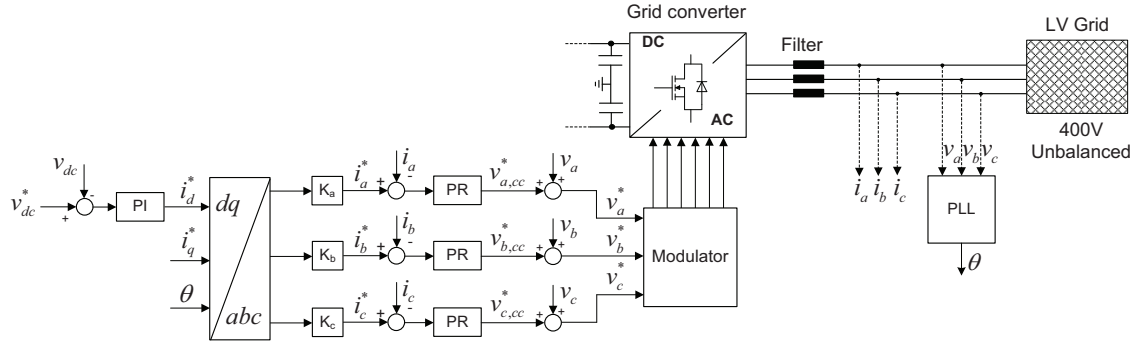

Figure 7: Stationary *abc* frame control with independent phase loading factors

The adjustments factor can be introduced to adjust the current sharing between the three-phases, namely: K_a, K_b, K_c. 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.

Reactive power and negative sequence compensating current is delivered in the limits of the available current reserve of the power converter. The highest control priority is the delivery of the power required by the heat pump. The current reserve available can be used to deliver reactive currents or draw more current from the phase voltage with the highest magnitude. Therefore, the saturation on the *d* axis current reference should limit these ancillary grid services enough to be able to safely deliver the heat pump power.

Test results

To verify the performance of the control strategies under investigation, a SiC back to back converter prototype was built. The switching frequency was set at 50 kHz, with sampling of control quantities once every switching period. The grid converter is connected to a three-phase programmable power supply through a 1 *mH* inductor. The emulated grid unbalance is set to 2%, and the measured voltages are shown in the first subplot of Figure 8. The grid voltage references was setup with the root mean square (RMS) values of $V_{g,a} = 230\,V$, $V_{g,b} = 234.6\,V$, $V_{g,c} = 225.4\,V$.

The converter operation using the *dq* control structure (Figure 6) with the AC component feed-forward is shown in the second subplot of Figure 8. The unbalance factor was set to $K_u = 15$, resulting in

asymmetric power drawn from the three phases. Results that from phase b with the highest magnitude, the RMS current drawn is 7.9 A, from the phase c with the lowest magnitude the RMS current is 6.6 A and from phase a with the average magnitude the RMS current is 6.9 A.
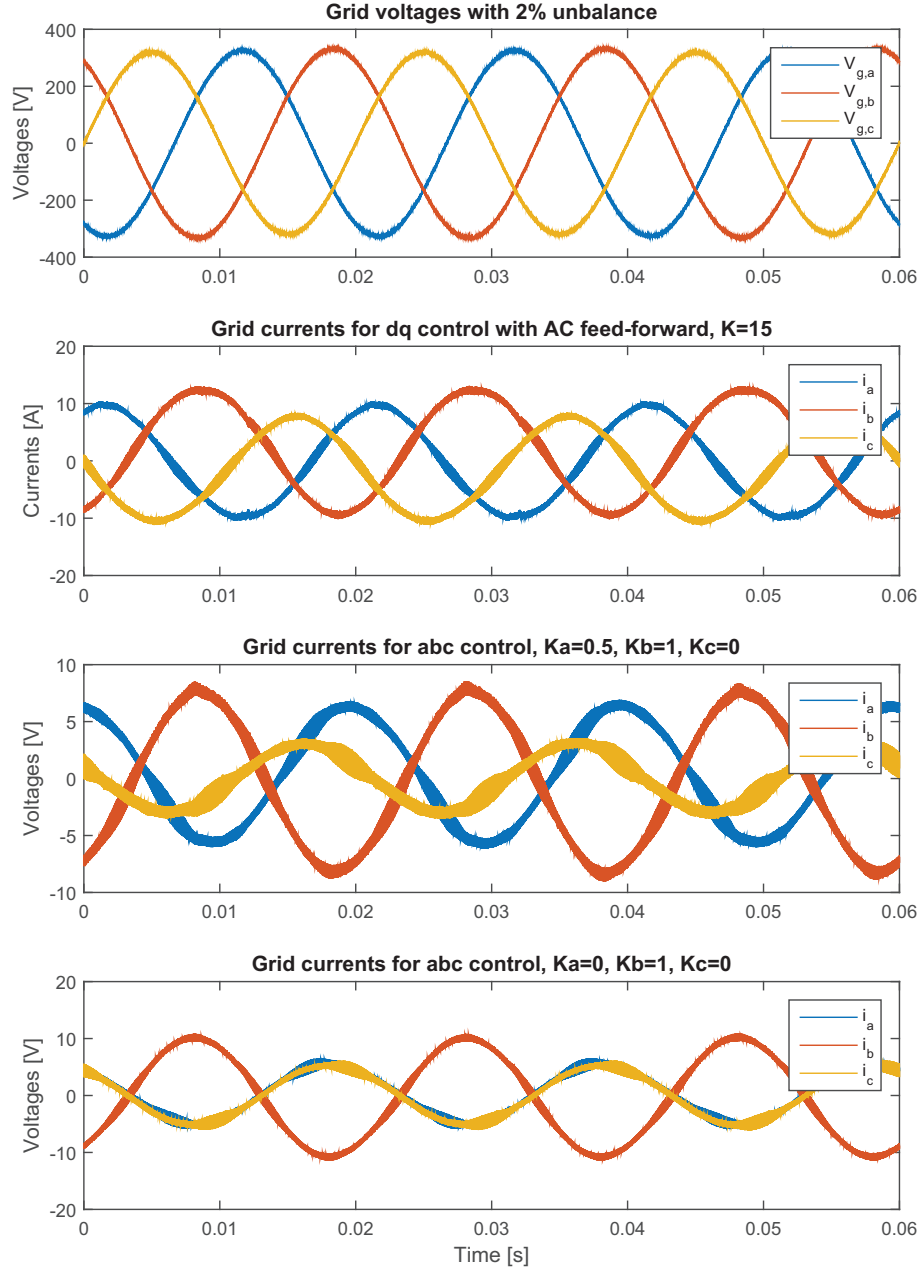

Figure 8: Experimental results: grid voltages with 2% unbalance; dq control with feedforward $K_u = 15$; abc control $(K_a = 0.5, K_b = 1, K_c = 0)$; abc control $(K_a = 0, K_b = 1, K_c = 0)$

The converter operation using the abc control structure (Figure 7) with current sharing factors for each phase is shown in the last two subplots of Figure 8. In the first case, the current is distributed according to the magnitude of the grid voltages drawing the highest current from phase b and the lowest from phase c. In this case the RMS values of the currents were $i_a = 4.3$ A, $i_b = 5.6$ A, $i_a = 2.2$ A when the current sharing factors were set to (0.5, 1, 0). The extreme case is when it is possible to draw the whole power from a single phase, as it is shown in the last subplot of Figure 8. The sharing factors were set to (0, 1, 0) and the resulting RMS current values were $i_a = 3.7$ A, $i_b = 7.4$ A, $i_a = 3.7$ A. It can be seen that in all

cases, no matter what the reference value is, the relation $i_a + i_b + i_c = 0$ is always valid in the measured currents as it is imposed by the three-phase three-wire plant.

Conclusions

This paper proposes the next generation heat pump converter and control structure. Controllable heat pump distribution loads are to be the first step in the transition to smart grids. To be able to provide grid support, a compressor drive supplied via a back to back converter is proposed. Building the power converter with SiC devices has the advantage that the converter design can be optimized in efficiency or power density. Moreover, the converter control can be realized with high bandwidth due to the possibility of switching with high frequency. Two control strategies were implemented and investigated on a SiC heat pump converter prototype. It can be seen that both strategies are able to load the grid in an opposing direction with respect to the unbalance in the grid voltage. The extreme case is when the whole power is drawn from a single phase, case possible only when operating with a heat pump load power of 30% or lower. For higher power required by the heat pump the amount of unbalance must be reduced enough to be able to safely deliver the power without overloading the power converter in current. Reactive power and voltage harmonic compensation can as well be implemented when using a back to back converter.

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