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Next Generation Heat Pump Systems with Enhanced Smart Grid Response Capability for the United States Market

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Abstract

Inverter driven, variable capacity heat pumps are being developed with an array of attributes that enable the heating & cooling electric load to be an integral part of an integrated energy network. Higher heating capacity and flexibility of heating supply air temperature, maintained at low outdoor temperatures, allows for heat pump use in traditionally fossil heated locations. Given the widespread historical use of fossil based heating in the northern tier of the United States, the new availability of heat pumps for this market segment could prove to be transformative. There are many market hurdles to such a transformation, starting with the inertia of the existing housing stock and the manufacturing and distribution networks of fossil based systems. In the southern tier of the U.S., higher heating capacity allows heat pumps to be deployed without need for secondary electric heat. This has profound implications for reducing winter peak loads in the southern states, which can in turn affect needs and design of the generation & transmission systems. Communications connectivity is another key attribute of advanced heat pump systems which enables flexibility of the electric load. Flexibility of delivered capacity, and the corresponding power draw, can provide a new tool for more effective demand response, in both the summer and winter. It can also be a tool for adapting to intermittent generation by renewable sources. This paper explores the potential of the next-generation of variable capacity heat pumps being introduced in the United States market, with the perspective of the electric utility system, for a variety of use-cases.

Keywords: variable-capacity, grid-connected, load control, backup heat control, demand response

1. Introduction

In 2009 there was much discussion about the coming Smart Grid as large dollar commitments for research & development were being pumped into the economy through various avenues from ARRA (American Recovery & Reinvestment Act) funding. “What is the Smart Grid?” was a common question, the answer to which depends on many diverse particular needs across the transmission, distribution and end-use electrical networks. In a most general way, the answer is that the Smart Grid uses information exchange to enable measurement and control to solve a grid problem or improve the grid state. Specific needs and implementations depend on many factors, very often geographically dependant, like load shape, generation mix, renewable generation penetration, age & loading

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of distribution feeders, load growth rate and many others. A primary reason for implementing a smart grid technology is to provide economic value to those who operate or use the electrical system—essentially all of us.

Air conditioning & heating is the primary load which drives consumption and peaking for the majority of situations on the electrical grid [1]. Because of their prominence of energy use, HVAC systems are a preferred resource for energy efficiency and load management for U.S. utilities.

Unitary air conditioners and heat pumps in the United States have been and remain primarily single speed machines, where the compressor and fans operate at fixed nominal speeds. System performance for fixed speed machines can be relatively easily mapped to externally imposed variables (independent variables), namely indoor and outdoor air conditions. Dependant system characteristics, like capacity, power consumption, operating efficiency (COP), and even more internal measures like refrigerant mass flow, are functionally dependant on a relatively small set of variables, and can thus be tested and mapped.

Operating in heating mode, the situation is similar with dependant variables being mapped to indoor temperature, outdoor temperature and outdoor humidity, though with one twist, frosting. Frosting occurs at certain combinations of outdoor coil temperature and outdoor air humidity content. The effect of frosting can be treated as a steady-state, though periodic behavior, which is still functionally dependant on the three primary independent variables. In the non-frosting regime, output variables will be steady over time, and in the frosting regime they will change periodically & repeatably.

Performance maps created by measuring outputs across a range of input variables provide an important and simple tool for predicting energy use for specific applications of heat pumps. One can simply apply the measured output (capacity, power draw…) to a known set of operating conditions for a particular building, and predict the total energy use over a period (day, season, year, etc.). This enables comparison of different heat pump classes with relatively ease. Modeling packages like those built on DOE-II and Energy Plus, apply this technique in combination with building load calculators and are widely used in industry for energy use prediction.

Standardized rating numbers like HSPF and SEER attempt to distil the performance map into a single number that characterizes overall heat pump performance. There is debate about how well a single number accomplishes this, but with somewhat acceptable accuracy, the ratio of rating numbers is a predictor of relative energy use.

For a similar class of heat pump, for instance residential split systems, the ratio of SEER or HSPF numbers can reasonably be used to predict seasonal energy use/savings. This technique forms the basis of many utility incentive programs for energy efficiency. It also forms the basis of the Consortium for Energy Efficiency (CEE) tier levels, which are used to define incentive program structure.

However, because of the way single-speed heat pumps operate, as steady-state producers of capacity at a known set of operating conditions, the rating numbers happen to be a somewhat accurate tool for relative energy use calculation. They have thus been successfully used for years as the primary determining tool for utility incentive programs.

Things change a bit when variable-capacity heat pumps are considered. When variation of system components is added to the mix, new degrees of freedom are introduced and hence, new independent variables are added. Whereas with single-speed performance mapping, there are three independent variables, with variable capacity there are many more. Compressor speed, evaporator fan speed, condenser fan speed and expansion orifice opening all become potential new independent variables. So too does the control strategy—how does the system respond to its driving input? In single-speed systems, a system turns on via dry contact, triggered by a differential on a thermostat. There is no proportional, or time dependant component to control. With variable capacity systems, there may be any mix of control strategies based on measured inputs like return and supply air temperature, and their respective time dependence relative to set point. The output function grows in complexity:

The flexible operation of variable capacity systems provides a variety of new system attributes and thus a new set of operating possibilities. This allows for creative applications in meeting HVAC loads, including application of heat pumps in traditionally fossil heated climates. It also enables possibilities for using real-time load variation to meet requirements of both traditional demand response programs, and for the creation of new measures that can capitalize on flexibility—such as renewable integration. Program and market structures for real-time flexibility at the end-use are evolving. The remainder of this paper summarizes two promising applications for variable capacity systems: the elimination of electric strip heat and advanced demand response.

2. Elimination or Minimization of Backup Electric Heat Operation

Proliferation of heat pumps into traditionally cold climates like the northern U.S. is perhaps the most promising technological step forward accommodated by variable capacity heat pumps. The traditional, single-speed heat pump is normally sized for cooling mode and gives what it can in heating mode, then is supplemented below the heating balance point with a secondary source, electric resistance or gas furnace. Variable capacity systems offer promise to produce higher heating capacity levels for a given nominal equipment size, primarily because they can operate the compressor above nominal speed. Though coefficient of performance (COP) is still dependant on ambient operating temperatures, it is possible to maintain COPs well above 1.0 (the effective COP of resistance heat) at outdoor air temperatures approaching and below 0°F (-18°C). Thus, if heat pump capacity can be throttled up by increasing compressor speed, the balance point can be pushed lower, sometimes to where no 2nd stage heat is required. Two cases are examined; one for mid-US locations and a second for Deep South US locations.

The first study by Bush [2] shows that an off-the-shelf variable capacity, split-system heat pump was able to maintain nearly 100% nominal capacity (at 8.3°C (47°F) outdoor temperature) down to -18°C outdoor ambient. A comparable single-speed system, acting as the baseline, produced 38% of nominal capacity at -18°C. The same study shows COP decreases at approximately the same rate for both systems (with decreasing outdoor temperature), but remaining above 1.5 for both systems down to -18°C.

The study modeled several heat pump types in a typical residential load profile for several U.S. cities, including: Atlanta, GA; Kansas City, MO; and Cincinnati, OH. Atlanta typically has a moderate, southern winter climate, while Kansas City and Cincinnati experience colder winters, more typical of the northern and mid-western U.S. It was shown that application of variable capacity heat pumps to all three locations could significantly reduce the run hours of 2nd stage electric heat. In the Atlanta climate, need for electric heat was nearly eliminated with certain heat pump models, even without oversizing relative to standard sizing practice for single-speed systems. In Kansas City and Cincinnati, electric heat was reduced, but still required. Oversizing could likely significantly reduce or eliminate the need for 2nd stage heat engagement.

Although a heat pump can technically be designed and sized to accommodate extreme cold, and thus most of the U.S. geography, cost considerations may change the optimum value. In colder climates, a system that incorporates some level of 2nd stage heat, either electric resistance or fossil fuel, may be a preferred choice. In the Southern tier of the U.S., the winter low temperatures are warm enough and of sufficiently short duration that in many cases, variable capacity heat pumps can be deployed without need for 2nd stage heat.

The second study by Hunt [3] offers two example tests performed in Orlando, Florida of the Southern U.S. The residences had been heated with single-stage heat pumps equipped with 2nd stage electric heat which energized when indoor set point exceeded indoor temperature by >1.11°C (2°F). During cold periods—outdoor temperatures below ~0°C (32F)—extended running of the 2nd stage heat on single-speed heat pumps causes sustained high power draw. Similar widespread operation throughout the residential base across the region causes high system-wide power draw resulting in winter peak conditions on the grid. These occasional winter peaks can exceed summer peak levels. Figure 1 shows a power profile for a single-speed heat pump with electric resistance 2nd stage from one of the Orlando sites. Electric resistance, drawing ~10kW, operates for two periods of approximately 2 hours and 2.5 hours between 7:00 am and noon. This operation, on a system-wide basis, contributes to the system peak for the region. Extended call for resistance heat in this situation is typically caused by a morning reset of thermostats to a higher temperature, rather than a decrease in maintained indoor temperature below set point. The latter would indicate an inability of the heat pump alone to satisfy the steady-state space heating load, i.e. operation below the balance point. It is likely that there is a mix of systems at just above and just below the balance point when such winter peak events occur in this temperature range.

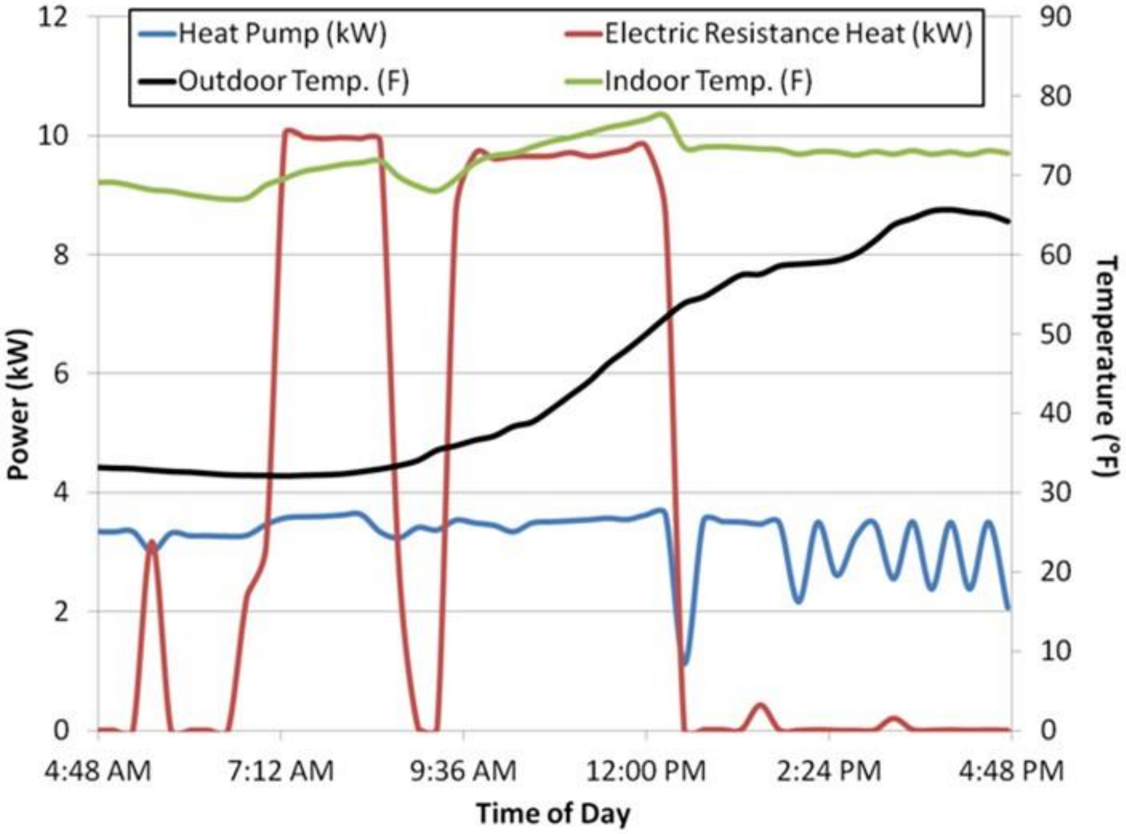

Figure 1: Residential HVAC Power Profile with Single Speed Heat Pump and Backup Electric Heat

Assuming that this behavior occurs at or around the balance point, then designing a system to satisfy the dynamics of the customers' heating needs requires a system with slightly higher capacity, to be able to ride through such morning events. The homes were retrofitted with variable capacity heat pumps. One was sized similarly to the baseline and the other was oversized by ~20%. Both were equipped with electric 2nd stage heat, with the intent of the study to understand the ability for runtime of electric heat to be reduced relative to baseline operation. Table 1 below gives a summary of the installations

Table 1: Single-speed vs. variable-speed heat pump test installations in Orlando [2]

Field Site	**Heating Load kW (Btu/h)**	**Cooling Load kW (Btu/h)**	**Sensible Cooling kW Load (Btu/h)**	**Baseline Single Speed Size kW (ton)**	**Variable Capacity Size kW (ton)**
Similar Sized	9.6 (32,681)	11.3 (38,464)	9.9 (33,924)	10.55 (3)	10.55 (3)
Oversized	13.2 (45,196)	15.1 (51,467)	13.8 (47,225)	14.1 (4)	17.6 (5)

Table 2 below shows relative run-time percentages for the oversized site. Both the baseline (single-speed) and retrofit (variable-capacity) heat pumps were equipped with 2nd stage electric heat, however, its operation was locked-out for the variable capacity HP, except for during defrosting. This was possible because of its ability to provide higher capacity at low operating temperatures. Oversizing (from 4 to 5 ton) nominally added 20% capacity. In addition, the variable speed nature of the system adds ~71% capacity at ~0°C compared to single-speed equivalents. Combined, this provided about 105% added capacity at 0°C.

Electric heat engagement in the -1.11-1.66°C (30-35°F) bin was reduced from 71% to 11%; where the 11% is fully during defrost operation. There were no points where the HP alone could not maintain indoor set point, or adequately provide capacity for a raised set point—such as for morning reset. For the similar sized system, there were reductions in electric heat use, but less so because its use was not locked out.

Table 2: Percent run-times for heat pump (HP) and backup heat for variable-speed heat pump vs. single-speed heat pump at Orlando, FL test site [3]

Outdoor Temperature Range (°C)	**Baseline Equipment**		**Variable Capacity Equipment**	
	HP	**Electric Heat**	**HP**	**Electric Heat**
-1.11 – 1.66	87%	71%	99%	11%
1.67 – 4.44	84%	40%	76%	4%
4.44 – 7.22	67%	29%	80%	1%
-1.11 – 7.22	74%	40%	81%	4%

3. Grid-Integrated Controllable Loads

Variable capacity heat pumps offer new possibilities for automatic end-use demand response. Across the U.S. there are several million residential air conditioners and heat pumps under various schemes of load control, the vast majority of which are relay mechanisms for temporarily limiting operation. These relay controls effectively act as duty-cycle limiters that override operation as otherwise determined by a system's thermostat. During demand response events, the capacity of the system is effectively turned off for a period of time, allowing indoor temperature and humidity to drift per the thermal loads on the house. This can lead to discomfort by occupants, and such demand response events typically have a provision for overriding by the occupants, to allow their system to turn back on.

Variable capacity air conditioners and heat pumps offer a potential for improvement in the traditional demand response approach. Rather than turning off completely, as in duty-cycle limiting, a variable capacity system can throttle to a state of lower power draw, but still maintain some level of capacity delivery. There are several potential advantages to such a strategy: 1) as a variable speed system is throttled—primarily by reducing compressor speed—power draw decreases faster than delivered capacity. This allows for less customer discomfort relative to power reduction, compared to a standard relay/duty-cycle strategy. 2) By maintaining some level of dehumidification during cooling demand response events, the rate at which the indoor space drifts toward discomfort is reduced. This may have the effect of extending the time for which a demand response event is tolerable by an occupant. Both of these effects point toward more available demand response for a given level of customer discomfort (or conversely, less customer discomfort for a given level of demand response) compared to traditional relay approaches on single-speed systems.

In order for variable capacity systems to realize some of these potential advantages, there must be a communications mechanism that enables them to work with demand response programs. One-way communication, through radio broadcast and powerline carrier are common methods employed for current relay-based installations. Though similar methods could be used to capture basic operation of variable capacity systems, there is an industry push to provide a more versatile and standardized, 2-way communication system for advanced air conditioners, heat pumps and other end-use devices.

Traditional heat pumps use true thermostatic control that closes relay contacts in response to temperature set point differential. Multiple stages can be employed to different levels of differential, but there is no time dependant component to control. Control is performed through dry contact of various relays in a 24VAC circuit. With variable capacity equipment, the 24VAC method is not generally sufficient to allow for proportional & time-dependant control algorithms, so manufacturers are employing various forms of proprietary 2-4 wire control/communications circuits between components of a heat pump. A variable capacity split system heat pump is no longer three discrete components—indoor unit, outdoor unit & thermostat, rather it is an integrated system that needs to be commissioned as a unit. What was a thermostat is now simply a user interface and may or may not contain any control circuitry.

The "thermostat" or now, more properly, the "user interface" for a VCHP may not be compatible with after-market devices. After-market programmable and more recently, communicating thermostats have become a staple of the energy efficiency and utility demand response practitioners' tool box, but they generally rely on the 24VAC system. Some manufacturers have created conversion kits or adapters that permit some functions of aftermarket thermostats to operate with variable capacity heat pumps. This remains an evolving part of the industry.

There are efforts throughout the greater appliance industry to enable "connected" devices, perhaps most famously in the EPA's Energy Star connected specifications. To realize true potential of VCHPs as a tool for flexible electrical load, the communication system and interface must be compatible with all the relevant features of load control. VCHPs could be designed to provide various versions load management options:

-Decrease power draw in response to request signal(s), or in response to inherent grid-state monitoring.
-Adjust power draw in response to availability of renewable generation.
-Provide fast-frequency response power draw adjustment for grid frequency and voltage control.
-Provide zone curtailment through a hierarchy or occupancy sensing algorithm.
-Provide customer ability to limit their power demand

There is an ongoing effort by the Air Conditioning Heating & Refrigeration Institute (AHRI) to develop a standard for communication with variable capacity air conditioners and heat pumps. Through efforts like this, more potential will be likely be unlocked from this new flexible line of space conditioning equipment.

4. Summary

The evolving product line termed "next-generation" heat pumps is a category of systems built on the core platform of variable speed compressors and associated components, which enables wide ranging flexibility of output—variable capacity. Variable capacity permits new approaches for application of heat pumps (inclusive of air conditioners) that takes advantage of inherent capacity flexibility, to provide better comfort while optimizing energy expenditure. The addition of communications connectivity permits the addition of other attributes to the core variable capacity system that then allows the systems' flexibility to be applied for a variety of additional use cases, including several approaches for advanced (more economical) demand response. The timing for the advent of these systems is excellent, as there is growing need in the power industry for flexibility. A burgeoning example is the transition to "neighborhoods of the future", where local generation and storage work in tandem with flexible loads on a neighborhood scale.

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