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Capacity control of heat pumps

In Sweden the current trend is to size heat pumps much closer to full coverage of the heating demand than has been the case so far. The driver for this development is both economic and legislative (increasing electricity price, possible power rates and limits in the building code regarding installed electric power for heating). This means that heat pumps will operate at part load almost all the time and that power utilization will be very low. This is particularly the case for new, low-energy buildings and has increased the interest in variable-capacity heat pumps. The article shows the importance of adapted electric motors, drives and control for good COP aslo in part load conditions.

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General aspects of capacity control

Capacity control, primarily by means of Variable-Speed Drive (VSD) motors, is commonly used to improve the efficiency of operation of systems for heating, cooling and ventilation. However, before going into the specific application of heat pumps it may be pertinent to look at some of the generic aspects.

Matching of supply and demand

HVAC systems are sized to cover a planned maximum design load, e.g. at the design outdoor temperature for heating or cooling or at the design polluting load for hygienic ventilation. Normal operation is at substantially lower levels, e.g. the ventilation rate in VAV systems rarely exceeds 30% of the design flow. This means that large energy savings are possible for heating, cooling and fan energy by capacity control of the fan motor. Theoretically this means that the fan motor should be optimized for a drive power that is around 30% of the design power in pressure-controlled systems and for only 5% of the design power in future, decentralized systems[1]. Similarly, a heat pump sized for full coverage has 80-90% of the operating hours at a capacity which is less than half the design power.

Demand starts at room level and a common experience is that use is larger than actual demand. This difference tends to increase when the load factor (i.e. power utilization) goes down. It is more difficult to control a small energy supply with a large power than with a small power. One way[1, 2] to accomplish the required load matching is by variable-speed drive (VSD) of compressors, pumps and fans.

Potential advantages with capacity control

Capacity control of heat pumps is interesting for several reasons. The most obvious is that reduced thermal power will lower the temperature differences in the evaporator and the condenser and thus potentially increase the coefficient of performance. Another effect is that the temperature swing in the heating or cooling system will decrease relative to the situation with on-off control. To achieve a given mean temperature of the room heater with on-off control the mean temperature during actual operation of the heat pump must be higher (lower in the case of cooling). Other examples[1, 2] of advantages with variable-speed capacity control are:

- fewer starts and longer operating times,
- reduced frosting and noise when air is used as heat source,
- possibilities to overrev the compressor and hence increase the capacity and avoid using a supplementary heat source,
- additional degrees of freedom in the control of sanitary water heaters etc.
- reduced latent cooling demand in refrigeration applications.

Variable-speed drive and motor efficiency

Although variable-speed drive of electric motors is a well-known technology it is less known, at least outside the circle of electric motor designers, that the matching of motor and controller type is critical for the end result. It is not uncommon to find retrofitted VSD equipment to existing motors that certainly deliver a reduced capacity but without substantial reduction of the drive power.

Motor torque and power requirements

A heat pump system comprises not only a compressor but also flow generators such as pumps and fans. The character of the mechanical work that these flow generators have to produce differs somewhat from that of the heat pump compressor and thus provides slightly different operating conditions for the respective motor and motor drive.

Pumps and fans

Heating and cooling systems typically use radial-type flow generators even though there may be axial fans in large systems and heat pump outdoor units. The torque requirement of this type of flow generator depends mainly on the flow character of the external system. Pressure drop has an exponential dependence on flow rate and we have the following relation (fully developed turbulent flow has $n \approx 2$):

$$\Delta p(\dot{V}) = \Delta p_0(\dot{V}_0) \cdot \left(\frac{\dot{V}}{\dot{V}_0} \right)^n \qquad \text{[Pa]}$$

where $\dot{V}_0$ is a specified reference flow rate (e.g. the design flow rate), $\dot{V}$ is an arbitrary, controlled flow rate and $1.7 < n < 2$ is the flow-related pressure drop exponent. Filters and some types of heat exchanger work in the laminar regime and hence have $n \approx 1$.

Torque is proportional to the pressure difference that the machine is working with and the power requirement $\dot{W}_p$ of pumps or fans is given by the product of torque and angular frequency ω of the rotating part. This means that the power requirement of the electric motor becomes (further details in an web-site article[1]):

$$\dot{W}_{e,p}(\omega) = \frac{1}{\eta_{e,m}(\omega) \cdot \eta_p(\omega)} \cdot \dot{W}_{p,0}(\omega_0) \cdot \left(\frac{\omega}{\omega_0} \right)^{n+1} \qquad \text{[W]}$$

Disregarding efficiency changes, the relation indicates that power as well as torque tends to zero as rotational speed (angular frequency) approaches zero. This is advantageous for the electric motor as it will start unloaded and thus have a very low starting current and this will also be advantageous from a grid perspective. Displacement type compressors, however, will have a very different torque characteristic.

Displacement compressors

Displacement compressors, e.g. piston, rotary piston, vane, Scroll and similar types, have a given transported volume V per revolution. In the case of a heat pump compressor the pressure difference will not primarily depend on the flow rate (compressor speed) but rather on the temperature difference between condenser and evaporator. The saturation pressures of the refrigerant in the condenser and evaporator, p_1 and p_2 respectively, depend directly on the condensing and evaporating temperatures t_1 and t_2. It is the temperature-related difference between condenser and evaporator that decides the torque on the compressor motor.

Fahlén[1] has shown that the torque of a displacement compressor depends primarily on the pressure ratio $\pi = p_1 / p_2$. The torque depends also on the absolute level of the evaporator pressure and therefore has a maximum at a certain inlet pressure. Depending on the operating conditions the compressor torque may vary from zero, with pressure-equalized start or the same temperature indoors and outdoors, to varying maximum torque in relation to pressure according to **Figure 1**. The power requirement of the compressor is obtained by multiplying the torque and the angular frequency (rotational speed).

Electric motors

The low efficiency of electric motors that appear in residential units has been an obstacle for achieving high seasonal performance factors. One reason for the low efficiency of ordinary asynchronous motors is that they will always draw a certain magnetizing current. No energy for useful work will be taken from the magnetic field and the magnetizing power will thus be a total loss. In particular during part-load operation this becomes significant; the magnetizing power remains more or less unaffected whereas the useful power is reduced. These effects are relatively more important for small motors than for large motors and thus the introduction of permanent magnet motors has had a tremendous impact for the development of more efficient small fans, pumps and compressors.

There are many alternative configurations for motors and motor drives but two alternatives are of special interest for small motors, the DC motor with permanent magnets and electronic commutation (EC = electronically commutated or BLDC = brushless direct current

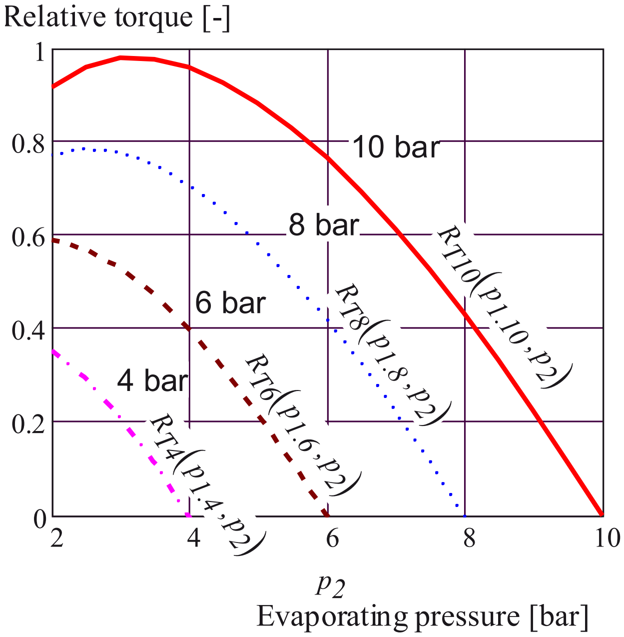

Figure 1. Relative torque T = T_{com} / $T_{com,0}$ as function of evaporating pressure p_2 with $p_1 = p_{1,0} = 10$ bar, $p_{2,0} = 2$ bar (see Fahlén[1]).

motor) and the synchronous AC motor with permanent magnets (PMSM = permanent magnet synchronous motor). They appear similar in their construction but the BLDC is fed by a rectangular-pulse current (pulsed DC) and the PMSM is fed by a sinusoidally varying current.

A heat pump sized for full coverage of the heating demand will deliver around 90% of the heat at a mean capacity less than half the design value and a very large part at less than 25% of the maximum motor power (varying conditions at the heat source and heat sink will make the motor power drop relatively more than the reduction in heating capacity). This implies that most operating hours will be at a very low relative capacity and to reap the full benefits of capacity control[1] it is necessary to conceive new systems[1, 3, 4] for heating, cooling and ventilation, to develop new components that can cope with large turn-down ratios while maintaining acceptable efficiency and finally to establish smart control strategies for the overall operation of the systems. As an example of recent developments at Chalmers/SP, **Figure 2** illustrates a comparison between three alternative motor topologies. The highest efficiency is provided by a new motor topology (PMSM) with matching drive and control and this prototype retains its high efficiency way down in the load range.

Heat pump application example

Figures 3 – 5 below illustrate the importance of matching the heat pump compressor control with adapted "parasitic powers" to pumps and fans while at the same time maintaining the efficiency of the electric motors.

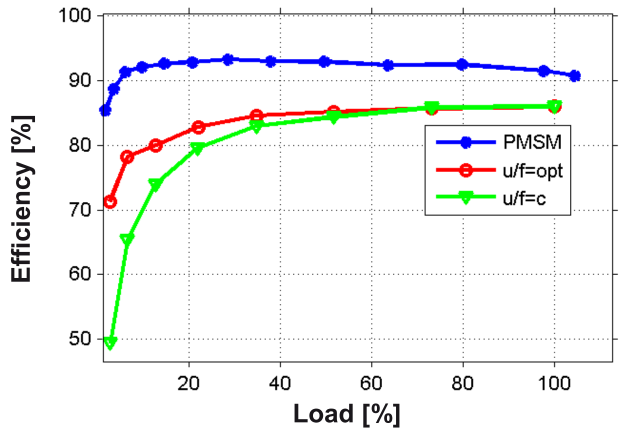

Figure 2. Comparison by Åström[4] of three alternative motor configurations. The two lower represent current state-of-the-art whereas the top curve is from a new PMSM motor developed by Åström.

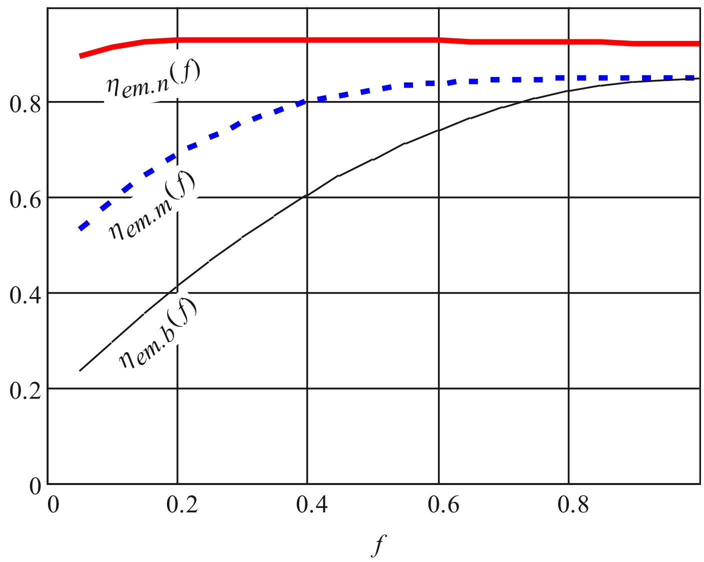

Figure 3. Motor efficiency (η_{em}) as a function of the fractional capacity (***f***). Index ***b*** represents a base case with today's standard practice, ***m*** corresponds to modern, state-of-the-art equipment and ***n*** is our newly developed concept (motor power around 1 kW).

The diagrams derive from development of a rotating air-to-air heat pump (an EU project where Chalmers and SP lead the scientific part). **Figure 3** presents a comparison of three alternative motor topologies that were used to simulate the coefficients of performance of the heat pump (COP_{hp}) and the heat pump system (COP_{hps}) respectively.

Figure 4 shows how the coefficient of performance of the heat pump system varies as function of the fractional capacity ($0 \leq f \leq 1$) at the operating condition +7°C outdoor temperature and +20°C indoor temperature. In

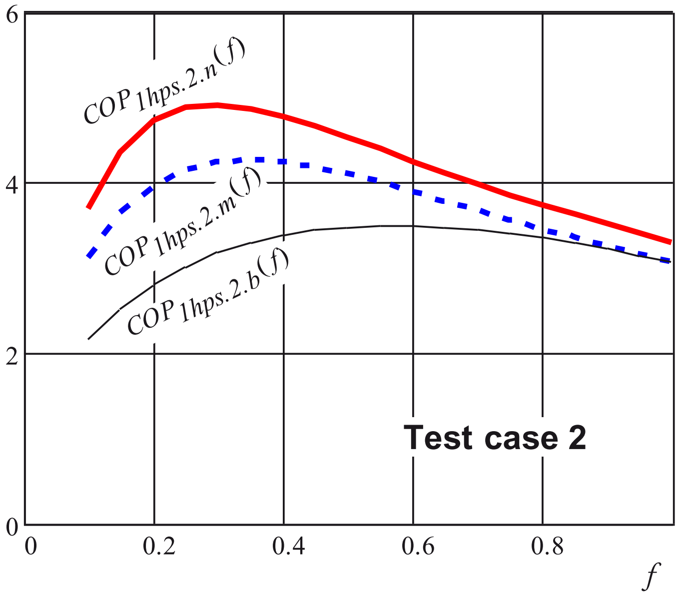

Figure 4. The coefficient of performance of the heat pump system (COP_{hps}) as function of the fractional capacity ($0 \leq f \leq 1$) for three alternative motor topologies. Powers to the evaporator and condenser fans are constant.

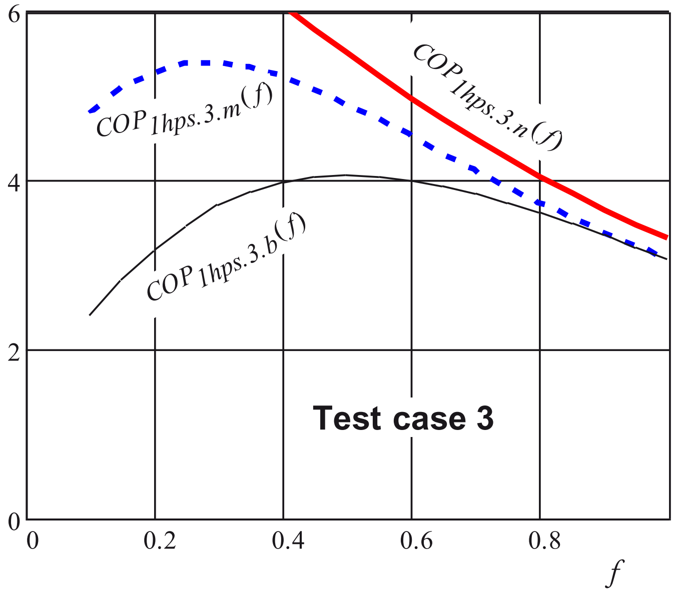

Figure 5. Coefficient of performance of the heat pump system (COP_{hps}) as function of the fractional capacity ($0 \leq f \leq 1$) for three motor topologies. Evaporator and condenser fan powers vary in relation to the relative thermal capacity.

this example the fans are uncontrolled with the implication that their powers become relatively more important in relation to the output of the heat pump. This also implies that with a sinking efficiency of the compressor motor the *COP* will not improve by much in the base case. The modern motor and our new concept, however, will provide substantial improvements.

Figure 5 provides the same comparison as **Figure 4** with the difference that also the powers of the evaporator and the condenser fans are reduced as the compressor power goes down. This also means that the air flow rates will drop in relation to the case of **Figure 4** and this will make the condensing temperature rise and the evaporating temperature drop compared to **Figure 4**. The reduction of fan powers, however, will be larger than the increase in drive power to the compressor and the end result is substantially improved part-load values for COP_{hps} in **Figure 5**. With the new motor technology, *COP* continues to increase all the way down to $f = 0.10$ and will then be an impressive 7.4!

Table 1. The heat pump system coefficient of performance of alternative system designs at 100, 50 and 20% load

(hps = heat pump system; 1-3 are the alternative system options; motor type: b = base, m = modern and n = new design).

Alternative	COP	$f = 1.0$	$f = 0.5$	$f = 0.2$
1. Constant evaporating and condensing temperature.	$COP_{1hps.1.b}$	3.1	2.4	1.4
	$COP_{1hps.1.m}$	3.1	2.8	2.2
	$COP_{1hps.1.n}$	3.3	3.2	2.8
2. Constant flow rates, constant fan powers. Decreasing temperature lift.	$COP_{1hps.2.b}$	3.1	3.5	2.8
	$COP_{1hps.2.m}$	3.1	4.1	4.0
	$COP_{1hps.2.n}$	3.3	4.5	4.7
3. Adapted flow rates, decreasing fan powers. Decreasing temperature lift.	$COP_{1hps.3.b}$	3.1	4.1	3.2
	$COP_{1hps.3.m}$	3.1	4.9	5.3
	$COP_{1hps.3.n}$	3.3	5.5	7.1

Table 1 provides an overview of the very large impact that system design, sizing and motor characteristic has on part-load performance.

Conclusion

The trend in the heat pump market is towards rising energy coverage. Higher electricity prices, the possibility of hourly tariffs and new power rates as well as new requirements in the building code affect the possibility of using electricity for peak heating (the standard alternative so far). Thus it comes natural to size all types of heat pump, ground-source systems in particular, as close to full coverage as possible by overreving the compressor on the coldest days. However, irrespective of application this article underlines the importance of adapted electric motors, drives and control.

References

See the complete list of references of the article in the html-version at www.rehva.eu -> REHVA European HVAC Journal