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Sizing strategy of on–off and modulating heat pump systems based on annual energy analysis

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ABSTRACT

In recent years the use of high efficient variable speed heat pumps has spread widely. Though several studies were carried out in the past comparing on–off and modulating strategies in heat pump units, only few works considered the whole heat pump system. Moreover, because of lack of knowledge about cycling losses, most of comparisons between modulating and on–off strategies did not consider the effects of the reduced coefficient of performance of a system at start-up. In this work simulations were carried out considering both on–off and modulating air-to-water heat pump systems in a single family house located in Italy. The aim of this study is to evaluate how the heat pump sizing, the thermal storage sizing and the cycling losses phenomenon can influence the annual energy performance of both the systems (on–off and modulating) and to investigate when modulating heat pump plants are actually more efficient than on–off.

Stratégie de dimensionnement de systèmes de pompe à chaleur tout ou rien et à modulation basée sur une analyse énergétique annuelle

Mots clés : Systèmes de pompe à chaleur ; Tout ou rien ; Modulation ; Vitesse variable ; Stratégie de dimensionnement

1. Introduction

In recent years the use of high efficient modulating heat pumps (equipped with inverter driven variable speed compressors) has spread widely. From the theoretical point of view several issues should be considered when a fixed speed heat pump (here referred to also as on–off heat pump) is compared to a variable speed one (referred to also as capacity controlled or modulating heat pump).

Peak load in building heating usually takes place only at the outdoor design temperature (e.g. −5 °C), that is for some tens

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Nomenclature

BLDC	brushless direct current motor
COP	coefficient of performance
CL	cycling losses [kJ]
K_p	proportional gain of PID control
PID	proportional, integral, derivative control
SPF	seasonal performance factor
T_c	condensation temperature [°C]
T_d	derivative time of PID control [s]
T_e	evaporation temperature [°C]
T_{ext}	temperature of the external air [°C]
T_i	integral time of PID control [s]
$t_{m,cycle}$	average water temperature at the condenser outlet during the on–off cycle [°C]
$t_{m,on}$	average water temperature at the condenser outlet during the on period of an on–off unit [°C]
$t_{m,off}$	average water temperature at the condenser outlet during the off period of an on–off unit [°C]
t_{wo}	water temperature at the condenser outlet [°C]
TEV	thermostatic expansion valve
TL	tank thermal losses [kJ]

of hours per year. If the selection of heat pump capacity is based on peak load, for most of the time heat pump capacity shall be controlled as it exceeds heating requirements; a fixed speed heat pump controls capacity by switching on–off. Undersizing an on–off heat pump with respect to the peak load lowers control requirements, however without eliminating them. Of course, undersizing heat pump capacity increases the number of operation hours of the auxiliary system (Lazzarin, 2012). As mentioned above, capacity control of a fixed speed heat pump gives rise to a sequence of on–off cycles that lower the efficiency of the unit. A variable speed unit, on the other hand, could run continually, so reducing the on–off frequency and the cycling losses phenomenon (Bagarella et al., 2013).

In principle, a modulating heat pump is more efficient than an on–off unit of the same nominal heating capacity. In fact, the same heating energy during part load operation is given by the modulating heat pump and by the on–off one, but the latter works only for a fraction of time, whereas the former operates continuously. Hence, the average temperature of the secondary fluid, during the on period, must be higher for the on–off unit to allow the due heat exchange. Fig. 1 depicts the typical water temperature profile at the outlet of an on–off heat pump unit. When the heat pump is activated (on period), the water temperature increases. As soon as the water temperature reaches the upper limit (whose value depends on the control settings) the unit is switched-off by the controller. Then, the water temperature decreases, due to the building thermal load. Finally, once the temperature reaches the lower limit (which also depends on the control settings) the heat pump unit is switched on again. In Fig. 1, the outlet water temperature of a modulating unit can be evaluated as the average water temperature of the on–off one ($t_{m,cycle}$) during the whole period, which is clearly lower than the average water temperature of the on–off unit during the on period ($t_{m,on}$). This will affect the condensation temperature the same way, leading the modulating heat pump to operate with a lower condensation temperature, then with higher *COP* (coefficient of performance, ratio of heating provided to work required).

From the previous rationale a meaningful increase in thermodynamic efficiency is waited when considering a variable capacity heat pump towards a fixed one. In fact, Aprea et al. (2006) compared an on–off air-water heat pump with a modulating unit and found a 20% electric energy reduction for the latter. Energy savings were mainly attributed to the reduction of the compression ratio during the modulation phase (Aprea et al., 2006).

However, a thorough energy analysis of the system shall consider the electricity needs of the inverter that equips a variable speed heat pump.

Though several studies (e.g. Aprea et al., 2006, Shao et al., 2004, Zhao et al., 2003) have been carried out in the past comparing on–off and modulating strategies in single heat pump units, only few studies (Adhikari et al., 2012; Cheung and Braun, 2014; Lee, 2010; Madani et al., 2011b) analyzed the whole heat pump system, which includes not only the single heat pump

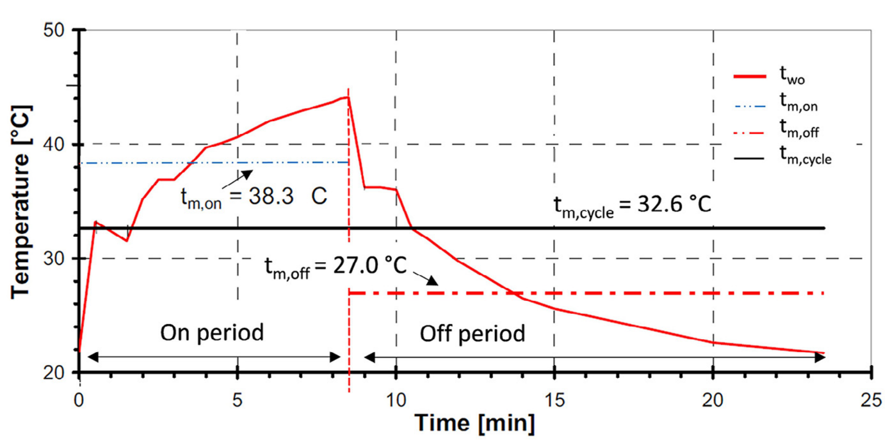

Fig. 1 – Outlet water temperature profiles in on–off heat pump unit (Fahlen and Karksson, 2005).