12[th] IEA Heat Pump Conference 2017

A strategy for the optimal control logic of heat pump systems: impact on the energy consumptions of a residential building

Matteo Dongellini[a]*, Massimiliano Abbenante[a], Gian Luca Morini[a]

[a]*Department of Industrial Engineering, School of Engineering and Architecture, Alma Mater Studiorum – University of Bologna, Viale del Risorgimento 2, Bologna, 40136, Italy*

Abstract

This paper presents a study on the effect of the modulation capacity of three different kinds of air-to-water heat pumps (i.e. single stage, multi-stage and inverter-driven heat pumps) on the seasonal energy performance of the heating system coupled to a typical single-family house located in Bolzano (Italy). The specific dynamic model of each heat pump and its control logic has been developed by using TRNSYS 17. These models are able to take into account the energy penalty linked to the on-off cycles by using experimental data obtained by the manufacturer of the selected heat pump units. A comparison of the energy performance of the HVAC system as a function of the heat pump typology is presented. Results highlight the strong influence of the control algorithm on the performance of the heat pump: it is shown that the multi-stage unit is unable to fully exploit its energy saving potential since its typical control logic is not able to reduce the number of start-ups during the warmer period of the heating season, when only one compressor is switched on. It has been demonstrated that dynamic simulation can be a valid tool for the optimization of the control logic of the multi-stage and inverter-driven heat pumps, in order to maximize the seasonal performance of the system and to minimize the number of on-off cycles.

Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Keywords: Air-to-water heat pump; control strategy; modulating heat pump; seasonal performance; on-off cycles.

1. Introduction

In recent years, the diffusion of air-to-water heat pumps has widely increased; this kind of system is a suitable solution to improve building energy efficiency, as imposed by a set of specific EU Directives [1-2]. The RES Directive [3] promotes the use of renewable energy sources and puts in evidence the potentiality of high-efficient HVAC systems: since the above-mentioned Directives consider aerothermal, geothermal and hydrothermal energy sources as renewable ones, heat pumps are good candidates to reduce the primary energy consumption of new and renewed buildings.

Nevertheless, the accurate evaluation of the energy savings achievable when heat pumps are used in a HVAC system can be a difficult task for the designers. In fact, the run-time performance of these devices depends by many parameters like the climate, the building thermal loads, the heat pump modulating capability, the hydraulic loop adopted to couple heat pump and emitters and its thermal inertia, the heat pump size and, last but not least, the multiple control logics adopted for each component of the HVAC system (i.e. fan coils, heat pump, circulating pumps and so on).

The aim of the present paper is to investigate the influence of different kinds of heating capacity modulation adopted by heat pumps on the energy efficiency of a heating system. It is well known that the modulating

* Corresponding author. Tel.: +39 0512090467; fax: +39 051 2093296.
E-mail address: matteo.dongellini@unibo.it.

capability of heat pumps strongly influences the seasonal performance of the HVAC system [4]. A single-stage heat pump modulates its capacity by means of a sequence of on-off cycles which generally decreases the energy performance of the device; on the other hand, multi-stage and variable-speed heat pumps could work continuously for a longer time interval during the season, switching the number of active compressors or changing the inverter frequency. In this way, these devices are able to reduce the frequency of their on-off cycles with respect to single-stage units, reducing the cycling losses phenomena [5].

In recent years, several researchers have compared numerically the annual performances achievable by single-stage and modulating heat pumps [6-8]. As an example, Cheung and Braun [6] proposed a method to analyze the performance of variable-speed air-to-air heat pumps and to compare the seasonal efficiency with those of traditional single-speed systems. The paper pointed out that modulating devices operate more efficiently with lower building thermal load. Bagarella et al. [7] presented a numerical study on the annual performance of on-off and modulating air-source heat pumps coupled to a single-family house. The analysis showed that the inverter-driven heat pump was characterized by better energy efficiency if compared to the on-off one and this advantage strongly depends on the size of the heat pump and the thermal inertia of the HVAC system. Finally, Dongellini et al. [8] developed a model based on the bin method and the building energy signature to calculate the seasonal performance of different kinds of air-to-water heat pumps (on-off, multi-stage and inverter-driven). The paper reported a series of sizing rules for HVAC designers and it demonstrates how modulating capability of the different heat pump typologies affects the optimal sizing of the system.

In this paper, a comparison between the seasonal efficiency obtained by adopting different kinds of air-to-water heat pumps coupled to the same building is carried out. The complete dynamic simulation of the HVAC system has been made by using TRNSYS 17 [9]; the TRNSYS models of on-off heat pumps (On-off HP), multi-stage heat pumps (MSHP) and inverter-driven heat pumps (IDHP) have been developed. In these models the penalty due to the on-off cycles in terms of energy losses and the reduction of thermal capacity and *COP* for each start-up have been taken into account according to manufacturer experimental data and the typical control algorithms adopted by the manufacturers for On-off HP, MSHP and IDHP have been implemented. These aspects have been only partially considered in the previous studies [4-8]. Several simulations have been performed coupling the above-mentioned devices to a single-family house. The impact of the different control strategies adopted for On-off HP, MSHP and IDHP is highlighted by the comparison of the seasonal energy performance parameters (*SCOP*) and the total number of on-off cycles made during a season.

2. Building characteristics and climatic data

The building considered in this paper is a typical single family house, built in the 90s located in Bolzano (Italy), and it is composed by a single floor. The main geometrical and thermo-physical characteristics of the simulated building are reported in Table 1: it is characterized by 162 m^2 net floor area and about 560 m^3 gross heated volume. As highlighted in Table 1 by the U-values of the main components of the building envelope, the insulation level of the opaque and transparent structures is typical of the construction period. The single-family house has been modeled by means of the plugin TRNBuild, within TRNSYS 17 environment; a total of 8 thermal zones have been implemented in the model. The layout of the building, linked to the indication of the considered thermal zones, is shown in Fig. 1; the house is composed by three bedrooms (R1, R2 and R3), two bathrooms (B1 and B2), a corridor (C), a kitchen (K) and a living room (LR).

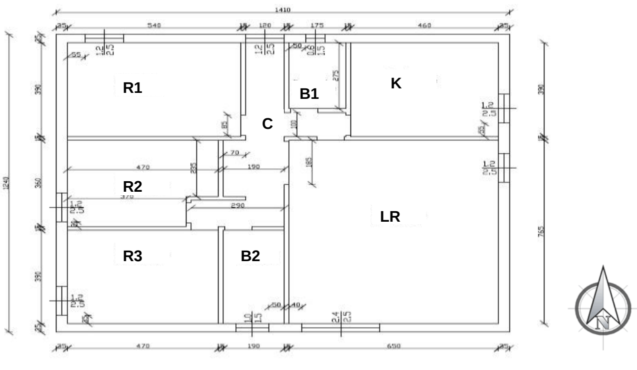

Fig. 1. Layout of the building with indication of the considered thermal zones

Table 1. Geometrical and thermo-physical properties of the considered building

Net floor area (m^2)	Gross volume (m^3)	S/V (m^{-1})	External wall U-value (W/m^2K)	Floor U-value (W/m^2K)	Ceiling U-value (W/m^2K)	Windows U-value (W/m^2K)	Ventilation rate (hr^{-1})
162	560	0.93	0.45	0.93	0.56	2.83	0.3

By means of TRNSYS the thermal load required by the building during the cold season and the total energy demand for heating have been evaluated by fixing the set-point of the internal temperature equal to 20°C and considering the heating system switched on 24/24.

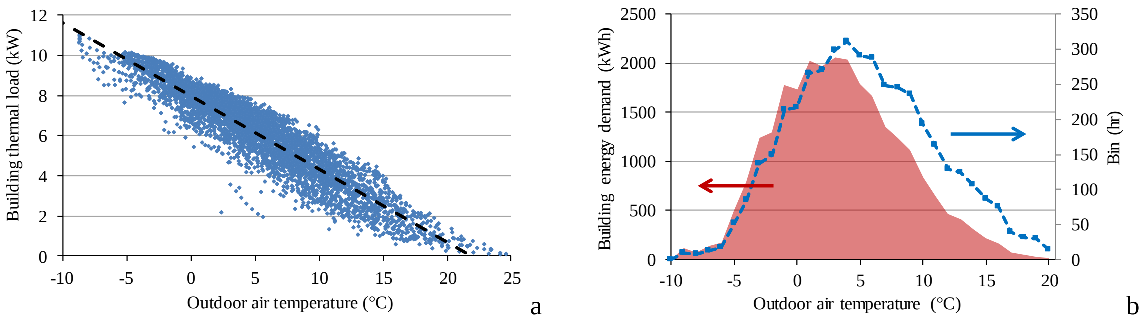

Fig. 2. Hourly building thermal load distribution with the highlighting of the Energy Signature (a), profile of the building thermal energy demand and bin distribution of outdoor air temperature during the heating season (b)

The building thermal load calculation has been performed by using the hourly climatic data included in the Typical Meteorological Year (TMY) of Bolzano. This TMY has been obtained from the Meteonorm database (version 5.0.13), included in TRNSYS 17 weather data file. According to the climatic data, the outdoor design air temperature is -9°C, corresponding to a building peak load of 11.1 kW. Since Bolzano is characterized by 2791 Heating Degree Days (HDD), current Italian Law [10] includes this location in the climatic zone E and its standard heating season lasts from 15th October to 15th April (183 days): the thermal energy demand of the building, evaluated for the above-mentioned standard heating period, is equal to 26312 kWh/year.

3. HVAC system characteristics

2.1 Sizing of the heat pumps

The HVAC system coupled to the building described in the previous section is based on a single electric air-to-water heat pump; no back-up systems have been considered because the heat generator has been sized on the building peak load. Three different air-to-water heat pumps have been selected (On-off HP, MSHP and IDHP) in order to cover the building thermal load during the whole winter season.

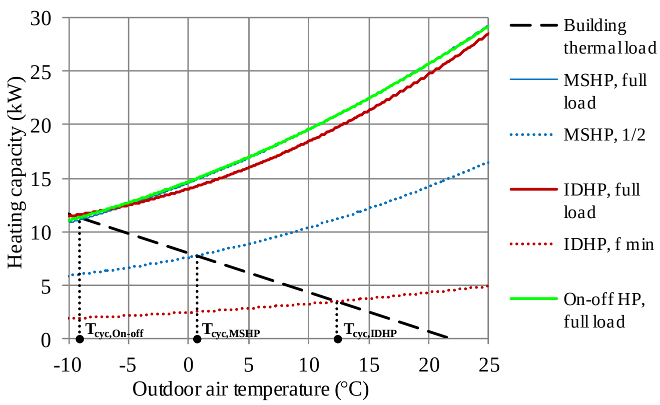

Fig. 3. Building thermal load, heating capacity at full load and at partial load for the considered heat pumps as a function of outdoor air temperature (heat pumps performance are evaluated for a hot water supply temperature of 45°C)

Fig. 3 depicts both the heat pump thermal capacities of the selected units and the building energy signature (black dashed line). By observing the continuous lines that represent the thermal capacity at full load of the units, it is evident that the selected heat pumps are able to overrate the load required by the building for the entire cold season: the size of the three units corresponds to a bivalent temperature close to -9°C, the design outdoor temperature of Bolzano. When the external air temperature is higher than the bivalent temperature, the heat pump thermal capacity exceeds the building thermal load and a modulating or an on-off control strategy is needed. It is evident from Fig. 3 that On-off HP will operate with on-off cycles during the whole season: according to the lack of any form of heating capacity modulation, the external temperature in correspondence of which the on-off cycling starts for this kind of heat pump ($T_{cyc,On\text{-}off}$) is equal to the bivalent temperature. MSHP considered in this paper uses two compressors; the thermal capacity modulation of this unit is linked to the possibility to switch on and off one compressor if the thermal load is reduced. In Fig. 3 the blue dotted line represents the MSHP heating capacity with one working compressor; the intersection between this line and the building energy signature fixes the temperature above which the multi-stage heat pump performs on-off cycles ($T_{cyc,MSHP}$ = 1°C). The selected MSHP avoids cycling losses for external temperatures between -9°C and 1°C.

Finally, the thermal power delivered by the selected IDHP at the minimum inverter frequency is shown in Fig. 3 (red dotted line). The selected IDHP is able to reduce its heating capacity up to 75% of the full load thermal power. Due to its enhanced modulation capability with respect to the other heat pumps, the variable-speed unit performs on-off cycles only for outdoor air temperature larger than 12.5°C ($T_{cyc,IDHP}$) which means that the selected IDHP is able to match exactly the building load for large part of the cold season.

2.2 Heat pumps performance

The selected heat pump models employ R410A as refrigerant fluid and are characterized by the same size, as evident by the continuous lines (blue, red and green) shown in Fig. 3 which represent the thermal capacity of the heat pumps at full load. The complete technical data at full load and at partial load, given by the manufacturer of these units, are reported in Fig. 4, Fig. 5 and Fig. 6 for On-off HP, MSHP and IDHP respectively. Data shown in Fig. 4 highlight that the heating capacity and *COP* of the selected On-off HP are strongly affected by the temperature of the hot water supplied to the building; as an example, by scaling from 45°C to 35°C the water supply temperature, *COP* increases up to 25%.

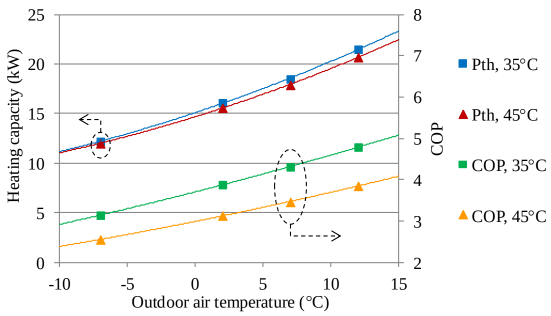

Fig. 4. On-off HP heating capacity and COP as a function of outdoor air temperature and supply water temperature

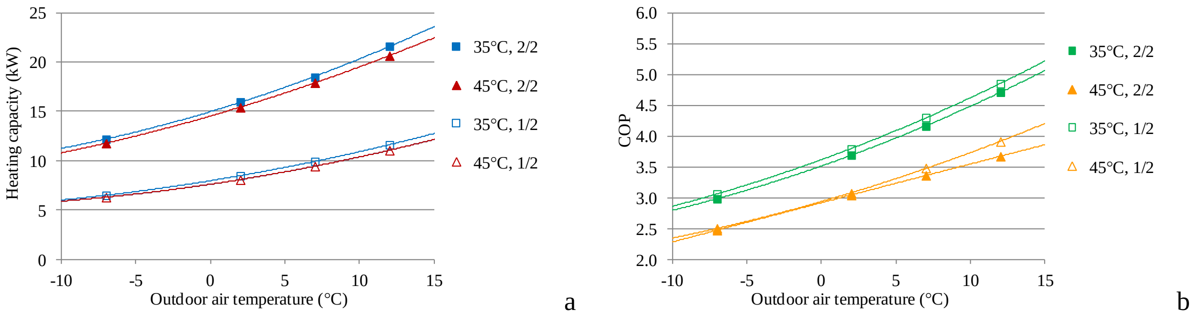

Fig. 5. MSHP heating capacity (a) and COP (b) as a function of outdoor air temperature, supply water temperature and number of compressors switched on

Data reported in Figs. 5a and 5b show that the heating capacity and *COP* of the MSHP are affected by the temperature of the hot water supplied to the building in the same way with respect to the On-off HP; on the other hand, the capacity to switch off one of its two compressors leads to obtain an enhanced energy efficiency at partial load, as highlighted by empty data series of Fig. 5b.

The selected IDHP uses a brushless DC scroll compressor and the modulation range of the inverter varies from 30 to 120 Hz. Heating capacity and COP of the variable-speed unit are reported in Figs. 6a and 6b, respectively. Fig. 6a shows that the heat pump heating capacity is proportional to the inverter frequency in the whole range of the outdoor air temperature. On the other hand, the maximum efficiency of the heat pump is obtained for frequency ranging from 40 Hz to 60 Hz: a similar result is reported in [7]. The COP increases up to 20% by scaling from the nominal frequency (120 Hz) to 50 Hz, depending on the outdoor air temperature.

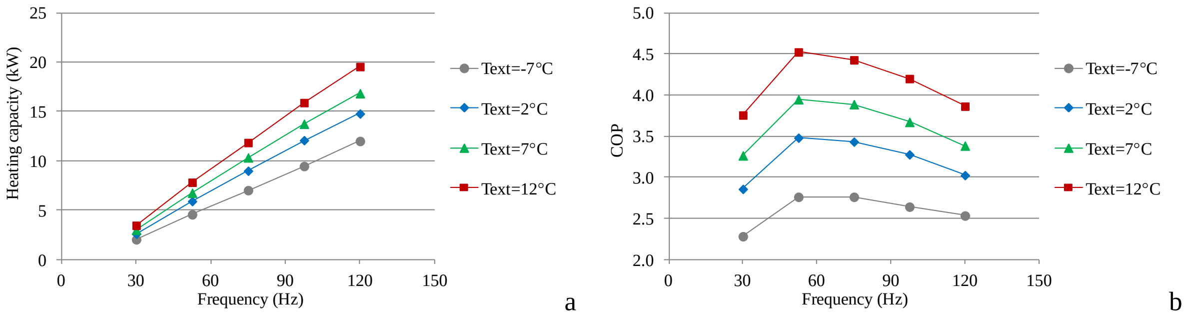

Fig. 6. IDHP heating capacity (a) and COP (b) as a function of outdoor air temperature and inverter frequency for a supply water temperature equal to 45°C

2.3 Heat pump control systems

Typically, the control unit of both On-off HP and MSHP employs the water return temperature ($T_{w,in}$) as monitoring variable for the modulation of the thermal power released to the building. On the contrary, IDHP is able to modulate its heating capacity by monitoring the water temperature at the exit of the heat pump ($T_{w,out}$).

Fig. 7a shows the logic of the control system adopted by the On-off HP. In order to avoid large variations of the water supply temperature to the terminal units, the heat pump works according to a 5 K dead band around the selected set-point for the return water temperature, imposed in this case equal to 40°C.

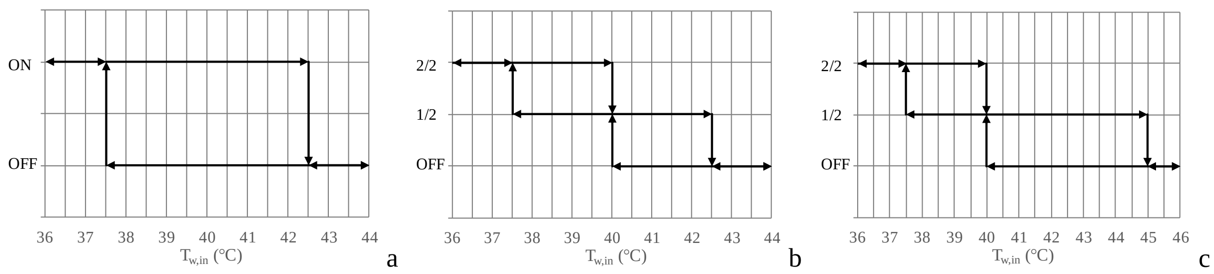

Fig. 7. Heat pump control strategy for On-off unit (a), MSHP (b) and $MSHP_{opt}$ (c)

The MSHP control system works following the behaviour shown in Fig. 7b. Since the MSHP is composed by two compressors, its controller uses two set-point values for the water return temperature and two dead bands. More in detail, the return water set-point temperature for the activation of the first compressor ($T_{SP,1}$) is 41.25°C, while the set-point for the second compressor ($T_{SP,2}$) is 38.75°C; both dead bands are wide 2.5 K. If the heat pump is switched off, when $T_{w,in}$ is lower than 40°C ($T_{SP,1}$ minus half dead band) the first compressor is activated. In this operating mode, the heat pump heating capacity could be higher or lower than the building thermal load; in the first case, $T_{w,in}$ increases and the heat pump is switched off for $T_{w,in}$ higher than 42.5°C, while in the other case $T_{w,in}$ decreases and the second compressor is activated when the return water temperature is lower than 37.5°C. Starting from the control algorithm reported in Fig. 7b, an alternative control logic has been considered for MSHP (Fig. 7c) which can be useful to reduce the on-off cycles when the device works at a reduced load (the behaviour of this control strategy ($MSHP_{opt}$) is explained in detail in Section 5).

For the selected IDHP a PID algorithm has been employed in order to set the inverter frequency in agreement with the thermal loads of the building. In this case the monitoring variable of the PID controller is the supply water temperature; the set-point value of the controlled variable is fixed at 45°C. When the minimum inverter frequency (30 Hz) is reached no further heating capacity modulation is possible; in this case on-off cycles are performed to match the building thermal load. The setting of the PID parameters has been assessed according to the manufacturer data: the values of the proportional gain K_p, the integral time T_i and the derivative time T_d have been set equal to 10, 300 s and 0 s, respectively (PI control).

Finally, in order to take into account the energy losses due to on-off cycles, a cycling penalization has been included in the dynamic model of the heat pumps according to the experimental results obtained by the manufacturer on the units selected in this work. At each start-up of the unit, the *COP* of the heat pump is reduced during the whole duration of the start-up period; this reduction is not caused by higher electric power absorption but by a decreased heating capacity of the heat pump during the starting transient. In fact, for each restart the compressor must restore the pressure difference between condenser and evaporator and for that reason the heating effect and the heating capacity of the unit gradually increase up to their steady-state values. Experimental tests conducted on the selected heat pumps have revealed that the steady state conditions in terms of absorbed electrical power and heating capacity are reached after different time intervals. More in detail, the start-up period for the electrical power input lasts for about 75 seconds and during this period the reduction of the power input is negligible (around 4%). On the contrary, the heat pump heating capacity reaches a stationary condition only after 150 seconds and during this transient period the unit average heating capacity is about 42% lower than the steady-state one. These data are summarized in Table 2.

Table 2. Start-up period and average reduction of electrical power and heating capacity during a starting transient of the heat pump

Start-up period of electrical power (s)	Average reduction of electrical power	Start-up period of heating capacity (s)	Average reduction of heating capacity
75	4%	150	42%

According to the above observations, the dynamic model of the heat pumps takes into account the cycling losses forcing the units to operate with a reduced electrical input power and a reduced heating capacity during each start-up. It is important to stress that the values reported in Table 2 are referred to the specific heat pumps models selected for this analysis and depend on the technology level of the adopted on-board control system.

However, this approach is suitable also with other heat pump models if experimental data similar to those reported in Table 2 are available.

2.4 Hydraulic loop and terminal units

The heat pump is connected to the terminal units (fan-coils) by means of a water single loop operating at constant flow rate. A thermal storage is connected to the exit of the heat pump in order to increase the thermal inertia of the hydraulic loop and to avoid high on-off frequency; in this case, a volume of 0.2 m^3 (equivalent to 11.2 l/kW) allows to limit during the whole year the frequency of the on-off cycles under 6 switches per hour, which is the maximum number of on-off startups suggested by the manufacturer.

The building terminal units are made up by two-pipe fan-coils, sized with a design supply temperature of 45°C on the base of the design load of each thermal zone. The technical data of the selected terminal units are shown in Table 3. The fan-coils are modeled in TRNSYS as a 3-speed fan and they operate with a constant water flow rate: when the fan is switched off a three-way valve bypasses the terminal unit and the hot water returns to the heat pump. The controller of the fan-coil automatically sets the fan speed on the correct level (off, minimum speed, medium speed or maximum speed) by monitoring the air temperature of the thermal zone in which the fan-coil is installed, to maintain the set-point value (20°C).

Table 3. Rated heating capacity, rated water flow rate and rated air flow rate of the selected fan-coils (data evaluated for air temperature equal to 20°C. inlet/outlet water temperature equal to 45/40°C and maximum fan speed)

Room	R1	B1	K	R2	R3	B2	LR
Rated heating capacity (kW)	1.81	0.52	1.72	1.48	1.68	0.63	3.35
Rated water flow rate (l/hr)	292	86	261	213	264	103	522
Rated air flow rate (m^3/hr)	271	123	271	233	271	145	497

4. Modeling

In order to calculate the seasonal efficiency of the considered heat pumps (On-off HP, MSHP and IDHP), the whole HVAC system was firstly modeled within TRNSYS environment. In Fig. 8 a schematic layout of the developed system is reported: it is evident that the heat generator is directly linked to the terminal units modeled within the green macros R1, B1, K, R2, R3, B2 and LR (single loop hydraulic distribution).

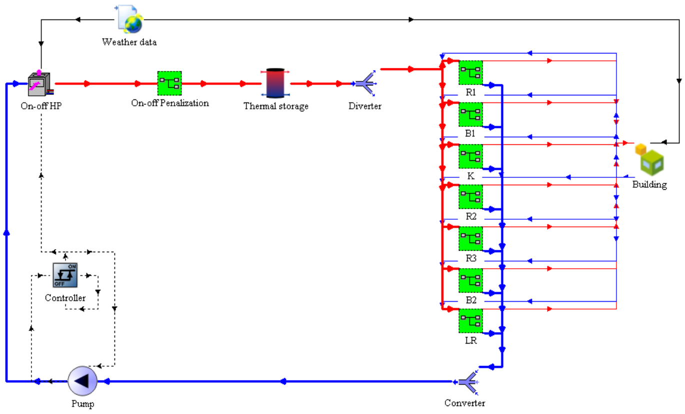

Fig. 8. Layout of the complete HVAC system developed within TRNSYS 17.

A specific TRNSYS model for each different kind of heat pump has been developed. More in detail, the performance of the on-off unit has been evaluated by using the Type 941, which is included in the TESS component library. However, the Type 941 has been modified in order to introduce the effect of the control system and the start-up energy losses. The selected MSHP has been modeled by means of two Types 941, the first one which simulates the full load working condition (i.e. two active compressors) and the second one which evaluates the performance of the heat pump with one compressor switched on. Finally, the mathematical model of the IDHP has been implemented in TRNSYS: the developed model considers the outdoor air temperature, the return water temperature and the inverter frequency as input data to calculate the performance of the heat pump and the supply water temperature as independent variable of the PI controller.

The logic of the control unit implemented in TRNSYS follows the algorithm used by the manufacturer for the different heat pumps considered in this work and described in the previous section. For the On-off HP the controller drives the on-off cycles of the device, while for multi-stage and inverter-driven heat pumps, the control unit allows the device to modulate its heating capacity by varying the number of compressor switched on (MSHP) or the inverter frequency (IDHP).

Dynamic simulations of the described system have been carried out by adopting a calculation time step equal to 1 minute; the whole winter season has been simulated in order to compare the seasonal performance of the HVAC system equipped with the three selected heat pumps. According to the Standard EN 14825 [11], the seasonal performance of a heat pump system during the heating season is evaluated by means of three indexes: the net Seasonal Coefficient of Performance ($SCOP_{net}$), the Seasonal Coefficient of Performance of the whole system ($SCOP_{on}$) and the seasonal efficiency for space heating (η_s), respectively defined as follows:

$$SCOP_{net} = \frac{E_{th,PdC}}{E_{el,PdC}}; \quad SCOP_{on} = \frac{E_{th,PdC}}{E_{el,PdC} + E_{el,pump}}; \quad \eta_s = \frac{SCOP_{on}}{2.5} \tag{1}$$

where $E_{th,PdC}$ is the thermal energy delivered by the heat pump during the heating season, while $E_{el,PdC}$ and $E_{el,pump}$ are the electrical energy consumptions of the heat pump and of the circulating pump during the heating season, respectively. In the definition of η_s the European primary energy conversion factor for electrical energy (equal to 2.5) is used [3].

5. Results

In Fig. 9 the daily on-off cycles performed by On-off HP, MSHP and IDHP are represented as a function of the daily average outdoor air temperature (grey, dark blue and red data series, respectively).

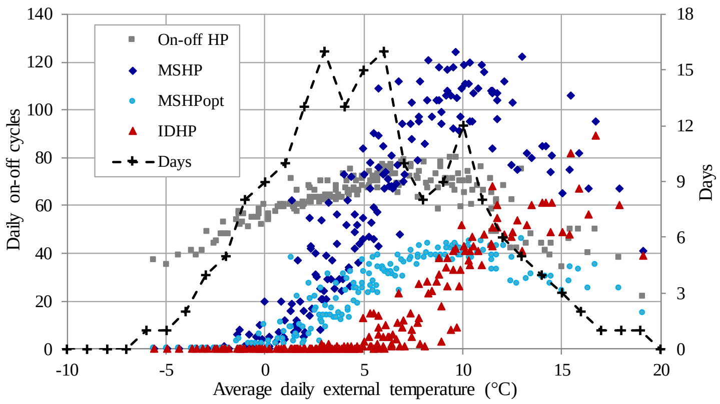

Fig. 9. Number of daily on-off cycles for the simulated systems with respect to the daily average outdoor air temperature

By considering the daily on-off cycles trend of the On-off HP it is evident that, as expected, this unit performs on-off cycles during the whole heating season. The on-off cycles trend presents a maximum of about 80 cycles/day for values of the daily average external temperature ranging from 0°C to 10°C; in correspondence of air temperature values lower or larger of this range the daily on-off cycles drop to 40 cycles/day. When the outdoor air temperature is lower, the building thermal load is higher and the average duration of the single on-off cycle increases because the "on" periods of the heat pump increase. On the other hand, when the building thermal load decreases (i.e. for higher outdoor air temperature), the average duration of the single on-off cycle decreases again due to the increase of the duration of the "off" period of the unit.

The trend of the daily start-ups evaluated for the MSHP presents several differences, if compared to the On-off HP. First, for seventeen days during the cold season (9% of the heating period), the MSHP avoids the use of on-off cycles: when the daily average external air temperature drops below -2°C, no on-off cycles are needed to match the building thermal load. When the outdoor air temperature ranges between -9°C and -2°C, the selected MSHP works alternatively with one and two active compressors, preventing any cycling losses. When the outdoor air temperature rises and exceeds $T_{cyc,MSHP}$ (in this case equal to 1°C, see Fig. 3) the multi-compressor unit activates the on-off control strategy; the number of daily start-ups increases and it reaches a maximum value of about 120 cycles/day in correspondence of a daily average air temperature equal to 10°C: above this value, the number of daily on-off cycles decreases due to the increase of the average duration of the "off" period of the heat pump when the building thermal load is reduced.

Results point out that when the MSHP operates outside its modulation range, it performs a higher number of on-off cycles with respect to the On-off HP: this is linked to the control system logic described in Fig. 7b; comparing Fig. 7a with Fig. 7b it is evident that MSHP employs dead bands that are the half of the dead band employed by the On-off HP and this is the main reason for which MSHP tends to operates with a higher number of start-ups with respect to the on-off unit.

This result suggests to adopt a different amplitude of the dead band for MSHP when the outside temperature is higher than $T_{cyc,MSHP}$ (in this case equal to 1°C) in order to reduce the on-off cycles of the unit. Fig. 9 shows that the adoption of the optimized control strategy ($MSHP_{opt}$) reported in Fig. 7c reduces the number of on-off cycles performed by the MSHP. When the outdoor temperature is lower than $T_{cyc,MSHP}$ the control logic of the unit does not change: the set-points for the activation of the two compressors are the same (i.e. 38.75°C and 41.25°C, see Fig. 7b) and the dead bands are both wide 2.5 K. On the contrary, when the air temperature is higher than $T_{cyc,MSHP}$, the water return temperature set-point for the activation of the first compressor rises to 42.5°C, while the relative dead band doubles to 5 K. The daily on-off cycles performed by the optimized MSHP reported in Fig. 9 as a function of the external temperature are strongly reduced, especially for large values of the outdoor air temperature.

By considering the daily on-off cycles trend for the IDHP, it is evident by Fig. 9 that this unit allows to avoid cycling losses for a significant part of the heating season: when the daily average external temperature is lower than 5°C, no on-off cycles are performed by the heat pump because the unit thermal capacity is modulated by varying the inverter frequency. Thus, on-off cycles do not occur for 82 over 183 days corresponding to the 45% of the heating period length. Moreover, results point out that the maximum number of daily start-ups of the variable-speed heat pump is close to 90 cycles/day; this value is obtained in correspondence to an average daily external temperature of 16°C. It is interesting to note that Fig. 3 suggests for IDHP the need of on-off cycles when the outdoor temperature is larger than 12°C (instead of 5°C as shown by Fig. 9). The achieved results underline that, especially when the thermal loads are strongly reduced, the "quasi steady-state" analysis obtained by comparing the building energy signature with the characteristic static curves of the heat pump can give an overestimation of the modulating capacity of the heat pumps. This result underlines the importance of the dynamic simulation for this kind of HVAC systems.

Table 4 reports the seasonal performance of the three heat pump systems considered in this paper. The differences in terms of *SCOP* are essentially due to the different modulating capability of the units: the results shown in Table 4 point out that the On-off HP is characterized by the lowest value of both $SCOP_{net}$ and $SCOP_{on}$ and by the highest number of on-off cycles during the heating season. The energy saving of the modulating units (MSHP and IDHP) with respect to the single-stage device goes from 6% for MSHP (8% for $MSHP_{opt}$) up to 18% for IDHP. The enhancement of the seasonal performance of capacity controlled systems is due to two main reasons: the *COP* improvement at partial loads (see Figs. 6b and 7b) and the reduction of the number of on-off cycles during the heating season.

Table 4. Seasonal performance of the HVAC system as a function of the heat pump typology

Heat pump typology	$E_{th,PdC}$ [kWh]	$E_{el,PdC}$ [kWh]	$E_{el,pump}$ [kWh]	$SCOP_{net}$	$SCOP_{on}$	η_s	Cycles
On-off HP	26159	9189	286	2.85	2.76	1.10	11393
MSHP	26420	8733	286	3.00	2.93	1.17	10335
$MSHP_{opt}$	26530	8595	268	3.09	2.99	1.19	4272
IDHP	26503	7864	286	3.37	3.25	1.30	2697

More in detail, the number of the heat pump start-ups decreases of about 9% and 76% for MSHP and IDHP respectively if compared with On-off HP: as pointed out by Fig. 3 and Fig. 9, the main difference between MSHP and IDHP is due to the larger modulation range in terms of outdoor air temperature which drastically reduces the need of on-off cycles for IDHP. The obtained results put in evidence that the higher the modulation capability of the heat pump, the higher the seasonal performance of the system.

Finally, in Table 4 it is possible to compare the performance of the different systems and to verify the impact of different control algorithms applied to the MSHP system. The adoption of the optimized logic strongly influences the total number of start-ups: during the whole season the amount of on-off cycles decreases up to 60% if compared to the typical MSHP control logic, limiting the compressor mechanical stress and the cycling losses. On the other hand, results point out only a slight increase of the $SCOP_{on}$ (+2%) with respect to the usual MSHP control logic: despite the strong reduction of cycling losses, the use of a wider dead band increases the average return water temperature (42.5°C versus 41.25°C) and the heat pump performance is lowered.

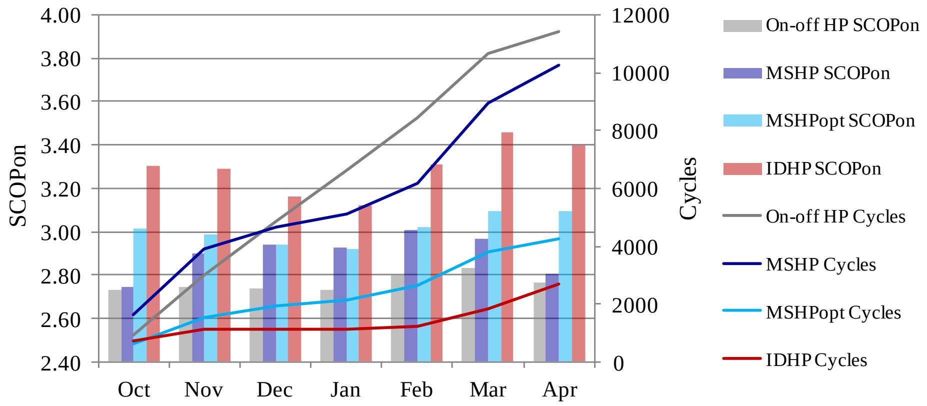

Fig. 10. Trends of the monthly values of $SCOP_{on}$ and cumulative on-off cycles for the considered heat pump systems

Fig. 10 represents the seasonal profiles of the monthly $SCOP_{on}$ of the selected heat pumps. It is interesting to observe that the modulating units are characterized by a variable slope of the cumulative on-off profiles. Fig. 10 puts in evidence how the IDHP is able to avoid the on-off cycles during the central months of the heating season (from November to February) while the MCHP only reduces the number of on-off cycles in the colder part of the season. Since the efficiency of the IDHP is only slightly affected by the number of heat pump start-ups, the energy performance of the system mainly depends on the outdoor conditions: the monthly values of $SCOP_{on}$ are lower during the colder period of the season and higher in correspondence of the milder months.

6. Conclusions

In this work a dynamic model of on-off and modulating air-to-water heat pumps coupled to a typical single family house located in Bolzano (Italy) has been presented.

The results show a significant increase of the $SCOP_{on}$ obtainable with the adoption of multi-stage and inverter-driven heat pumps with respect to the on-off unit (from +6% for multi-stage heat pump up to +18% for inverter-driven heat pump). The number of on-off cycles performed by the heat pump during the heating season is a significant value (linked also to the operative life of the unit) which is strictly correlated to the $SCOP_{on}$ of the system, especially for heat pumps sized on the maximum building thermal load, in order to avoid the use of additional backup systems. It has been demonstrated that the on-off heat pump performs the same number of on-off cycles per day during the whole season; on the contrary, the multi-stage heat pump avoids the use of on-off cycles during the most severe period of the heating season but in milder months this unit is characterized by a daily on-off frequency up to 50% higher than the one of the on-off heat pump, due to its reduced control dead band (linked to the number of compressors). In order to minimize this problem, simulations have been carried out by considering an optimized MCHP control logic, able to enlarge the controller dead band only for outdoor air temperatures above $T_{cyc,MSHP}$: the adoption of this control algorithm allows to drastically decrease the number of on-off cycles up to 60%. About the inverter-driven heat pump, according to its enhanced modulation capacity, it is able to avoid on-off cycles for 45% of the duration of the heating season, which allows to reduce the total number of on-off cycles up to 76% with respect to the single-stage heat pump.

References

[1] European Commission, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings, 2010.
[2] European Commission, Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC, 2012.
[3] European Commission, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the use of energy from renewable sources, 2009.
[4] Wu W, Shi W, Wang B, Li X. Annual performance investigation and economic analysis of heating systems with a compression-assisted air source absorption heat pump, *Energy Conversion and Management* 98 (2015) 290-302.
[5] Bagarella G, Lazzarin R, Noro M. Annual simulation, energy and economic analysis of hybrid heat pump systems for residential buildings, *Applied Thermal Engineering* 99 (2016) 485-494.
[6] Cheung H, Braun J. Performance comparison for variablespeed ductless and single-speed ducted residential heat pumps. *International Journal of Refrigeration* 47 (2014), 15–25.
[7] Bagarella G, Lazzarin R, Noro M. Sizing strategy of on-off and modulating heat pump systems based on annual energy analysis, *International Journal of Refrigeration* 65 (2016) 183-193.
[8] Dongellini M, Naldi C, Morini GL. Seasonal performance evaluation of electric air-to-water heat pump systems, *Applied Thermal Engineering* 90 (2015) 1072-1081.
[9] Klein SA et al. TRNSYS 17: A Transient System Simulation Program, Solar Energy Laboratory, University of Wisconsin, Madison, USA, (2010).
[10] Office of the Italian Republic President, Decree of the Italian Republic President D.P.R. No. 412/93, Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, Italy (1993).
[11] European standard EN 14825:2013, Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling – Testing and rating at part load conditions and calculation of seasonal performance, 2013.