Development of an advanced control system for chillers

CASE STUDY

Technology & Evolution

Presentazione di un sistema di controllo avanzato per chiller con compressore scroll ad inverter e comparazione con un sistema tradizionale ON/OFF

Nell'ottica dell'ottimizzazione energetica dei circuiti frigoriferi, ed in particolare di quelli ad espansione diretta, CAREL da sempre studia soluzioni di controllo che sfruttino le nuove tecnologie disponibili sul mercato.

Lo studio si propone di caratterizzare un'unità chiller acqua - aria per il condizionamento dotata di compressore scroll comandato tramite inverter e valvola di espansione elettronica.
Oltre a fornire una completa gamma di dati di funzionamento del compressore in tutte le condizioni di lavoro, sia di carico termico che ambientali, verrà presentato il sistema di controllo avanzato che sfrutta le potenzialità di regolazione continua e coordinata del compressore e della valvola elettronica, con lo scopo di evidenziare il risparmio energetico derivante dall'ottimizzazione del funzionamento della macchina nei confronti di un sistema tradizionale con compressore non modulante e sistema di espansione meccanico.

Infatti, la possibilità di regolare il flusso di refrigerante nel circuito e la resa del compressore contemporaneamente ma indipendentemente l'uno dall'altra, permette di ottimizzare il funzionamento della macchina e di renderlo adattabile ad ogni condizione di lavoro.
Per questo studio, l'unità è stata fornita di sistemi di misura di portata (acqua e refrigerante), di un sistema di misura dell'assorbimento elettrico (wattmetro) oltre che di sistemi di controllo della portata, della temperatura del carico e della temperatura e umidità ambientali.

Abstract

This work aims to provide a complete definition of a water-air chiller, featuring an inverter driven scroll compressor and an electronic expansion valve.
The first step involves recording all the operating data from the compressor in all possible working conditions.
As a second step, we will describe a new advanced control system, based on stepless regulation communication between the compressor control algorithm and the electronic valve control, in order to obtain significant power savings due to the optimised operating behaviour of the units. In this way, the possibility to control the refrigerant flow in the circuit and the compressor cooling capacity both simultaneously and independently allows the unit to work with maximum efficiency in all conditions. This power balance will also be compared against the consumption of a standard on-off unit

Introduction

Variable speed compressors can provide great power savings in the control of air conditioning units. The reduction in cooling capacity has a great impact on the unit control system especially regarding compressor and water limits and unit stability generally. To manage a chiller unit with variable cooling capacity, all the controlled devices must be considered together with the control system itself, as "communication" between devices can certainly avoid hunting problems.
We have developed a chiller control system that can take all the advantages of the complete control of inverter driven compressor, electronic expansion valve and condenser fans to maximize unit performance in all working conditions.

Chiller unit description

Unit type: water - air chiller heat pump.
Refrigerant: R407 C
Nominal cooling capacity: 16 kW (Tcond = 40 °C, Tevap = 4 °C, 75 Hz, Sh = 10 °C, Sbc = 10 °C)
Compressor type: inverter driven scroll compressor, 5 Hp
Inverter type: multi purpose 3-phase inverter, 380 to 460 V ±10%, 50/60 Hz ±5%
Condenser type (chiller): finned coil
Evaporator type (chiller): plate
Primary expansion device: stepper motor electronic expansion valve
Secondary expansion device: thermostatic valve

A water tank has been installed to control the load power at the evaporator.

The water flow at the evaporator is controlled in a simple water circuit with a bypass valve and measured with a flow meter, while the water temperature is controlled by 4 heaters with solid state relays.
In this way we can simulate all water conditions and load powers for the unit.

The chiller unit has been installed in a climate chamber that can reach ambient temperatures between 15 °C and 35 °C. All the other ambient conditions have been simulated using a calculated condensation profile. We have considered a unit working with fans at constant maximum speed (maximum efficiency) so that for each ambient temperature there is a precise target condensing temperature.

Data acquisition system

The unit has been fitted with 8 temperature probes (Pt1000 sensors) and 8 pressure probes (ratiometric pressure transducers) installed at each component inlet and outlet in order to appreciate both pressure drops and temperature conditions.
In this way we can draw the complete refrigerant cycle on the P-H diagram.
Temperature probes have also been installed to measure water inlet and outlet temperatures and condenser air temperatures.
For the measurement of the power balance we installed a water flow meter, a refrigerant mass flow meter and a wattmeter measuring compressor power consumption (including inverter power supply).
Even though we can easily calculate the actual power consumption of the heater for water temperature control (duty cycle of 2 identical pairs of 10kW heaters), we preferred to install a voltage measurement and 3 CT probes to measure actual power absorption of the heater.
Of course, this measurement needs to be correctly integrated, as the signal has a duty cycle.

The data acquisition software was developed on a PC-windows platform, based on National instrument Labview 6i, and communicates all the acquired and calculated data (i.e. saturated temperatures) to the main control program for chiller and water control, based on the same programming tool.

All data are acquired with a cycle time of 0.5 sec, and the historical recordings are saved to an Excel file every 5 sec.

Control system

The chiller control algorithm is made up of 4 different parts:
- compressor control (with or without inverter) according to the water temperature;
- electronic expansion valve control according to the superheat value;
- condenser fan control according to the saturated condensing temperature;
- prevention and alarm procedures.

Compressor control

To perform comparative tests we developed a control system that can work both with or without the inverter. Both types of control follow water temperatures (inlet or outlet), however control with the inverter requires an algorithm for the frequency.

We also have the possibility to simulate an on-off duty using the inverter at fixed frequency.
- *ON-OFF Duty and parameters*
  The compressor control has a simple water temperature set point with a differential that has to be reached to start the compressor again. Default values for our tests set the water inlet temperature at 12 °C with a 2 °C differential.
- *INVERTER Duty and Parameters*
  The compressor control has a PID algorithm according to the inlet (default) or outlet water temperature. The inverter frequency is increased or decreased to reach and maintain a water set point (in °C).

We designed a control algorithm with PID parameters to optimise firstly the water temperature stability and then the fastest duty temperature achievement.

When the unit is started the initial frequency is calculated proportionally, with the difference between the actual water temperature and the set point.

The compressor is stopped when the inverter frequency goes below the minimum value (default 25 Hz).

Condenser control

The condenser control has the same PID function as the compressor. The fan speed is controlled according to the condensing temperature set point. The main difference between the parameters is the correlation between input and output signal.
Water temperature decreases with increasing compressor frequency (any other parameter should of course be constant) with a linear correlation. The increase in the compressor frequency is constant. Condensing temperature is correlated with fan speed, which has a cubic correlation with the voltage signal from the control. For this reason, the increase in fan voltage has a quadratic correlation with the voltage itself. We can calculate this using the last value of the fan voltage.

Electronic valve control

The electronic valve is driven by a standard control device developed to move a stepper motor valve according to the superheat set point measured by 2 probes installed at the evaporator outlet. The first probe measures the evaporating pressure, the second one measures the superheated gas temperature. The control device is a stand alone instrument that communicates the input probe values, valve position, control parameters and status with the unit main control (PC).
The main superheat control has a PID algorithm working just with the superheat and set point. However, there are many different situations in which the unit working conditions are critical (low superheat, high condensing or evaporating pressures, low evaporating pressure).
In these cases it is important to have a control algorithm that can change the standard behaviour of the electronic valve to prevent the unit from stopping due to high or low pressures or from working in critical conditions for the compressor.
In many situations there is the possibility to change the superheat set point or even better to change the valve control according to the probe values, to decrease or increase refrigerant flow and cooling efficiency in order to keep the unit working even in difficult conditions (heavy load, very high outside temperature)
The valve control algorithm provides protection functions for all the unit warning situations (low superheat, high condensing temperature, low or high evaporating temperature) that can be avoided by adjusting the valve position.
There are 4 different limits:

- Maximum Condensing Temperature (59 °C)
- Maximum Evaporating Temperature (18 °C)
- Minimum Evaporating Temperature (-3 °C)
- Minimum Superheat Value (3 °C)

Prevention and alarm control

The prevention algorithm has significant influence on the behaviour of the unit, as it can manage the same critical situations listed for the valve control, but controlling the compressor frequency directly. There are 4 different prevent limits and naturally then 4 alarm limits that stop the unit.

- Condensing temperature (prevent 61 °C, alarm 65 °C)
- Evaporating temperature (prevent -5 °C, alarm -8 °C)
- Compressor discharge temperature (prevent 120 °C, alarm 125 °C)
- Water outlet temperature (prevent 3 °C, alarm 2 °C)

In all the prevent conditions, the inverter frequency is decreased with a defined step as soon as the prevent limit is reached, and then proportionally depending on the difference between the actual temperature or pressure values and the prevent limits.

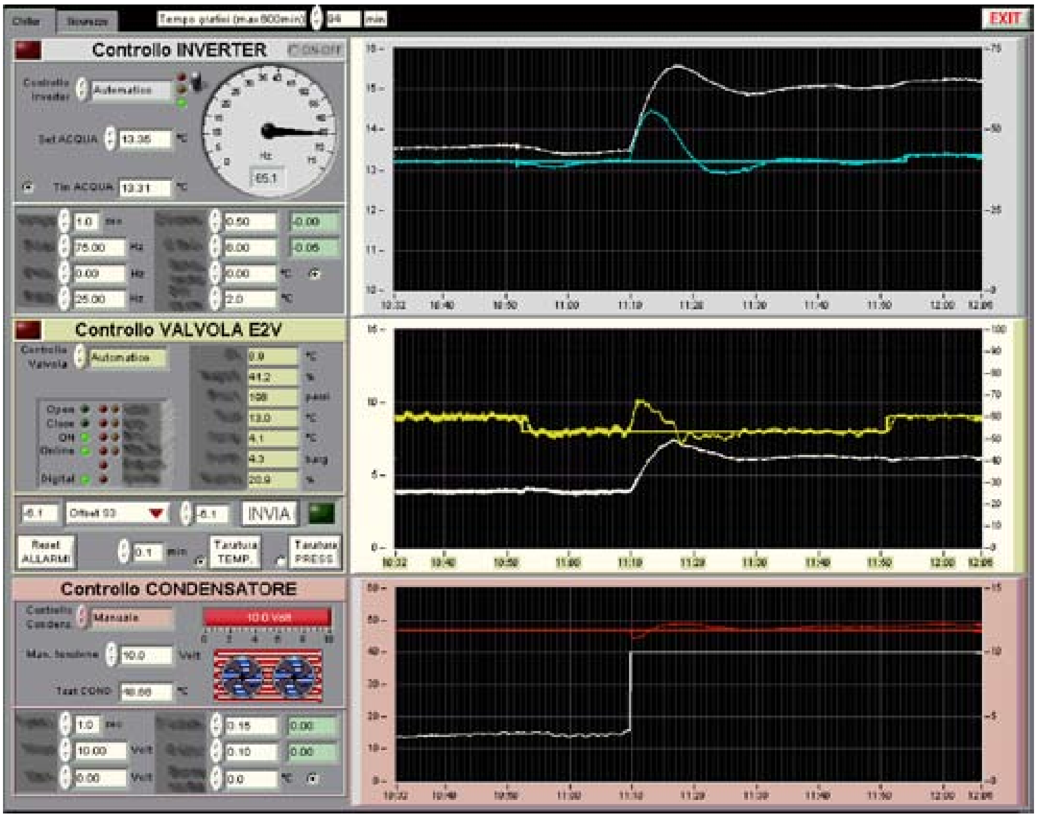
We are developing a calculation model that case-by-case can evaluate if these warning conditions have to be managed by changing the valve control or decreasing the inverter frequency (and cooling capacity). We expect there will be the possibility to set the behaviour of the unit in “maximum cooling capacity” or “maximum efficiency (COP)” mode.

Water Control

The control of the load power is completely separate from the control of the unit, to avoid any kind of mutual influence. Of course they both read and use the same temperatures from the data acquisition program.

The temperature control works with PWM (5 sec duty cycle). We can both select direct control of the load power (in kW) with a feedback measurement of the actual total power consumption of the heaters, or set a water temperature in the tank (which corresponds to the inlet water temperature of the chiller unit) with the same PID algorithm as the compressor.
The control algorithm reads the water temperature and modulates the PWM signal from 0% to 100% (0 kW to 20 kW) to reach the set point.
We can also automatically set the water temperature or power profiles to simulate different load conditions.

Figure 1 shows the control system front panel with the control parameters and a sample of chiller control in the graphs on the right (coloured lines are input variables and set points, water temperature, superheat and condensing temperature, while white lines are output variables, inverter frequency, valve position and fan voltage).
In the example we can see the control reactions during a variation in the load power.
The water temperature starts rising and the PID inverter control reacts to maintain the water set point (13.35 °C).
The control algorithm increases the inverter frequency from 45 Hz to 65 Hz and both the valve and condenser control follow the variation in the load. We can also see some changes in the water and superheat set point.



Set ACQUA 13.35 °C

Tin ACQUA 13.31 °C

Controllo Inverter Automatico

Controllo Valvola Automatico

Controllo Condens. Manuale

Max. tensione 10.0 Volt

Fig. 1: Control system front panel during inverter control

Inverter control characterisation

One of the first and more important advantages using an inverter driven compressor regards the condensing pressure related to power consumption: comparing with ON/OFF duty, the inverter control modulates the compressor frequency at lower values. This means lower condenser load and consequently lower condensing temperature with constant ambient temperature.
Figures 2 and 3 show the different power consumption at the same ambient (20 °C) and load conditions (40...100%). As the load decreases, the inverter frequency also decreases, and we can lower the condensing temperature and related power consumption.

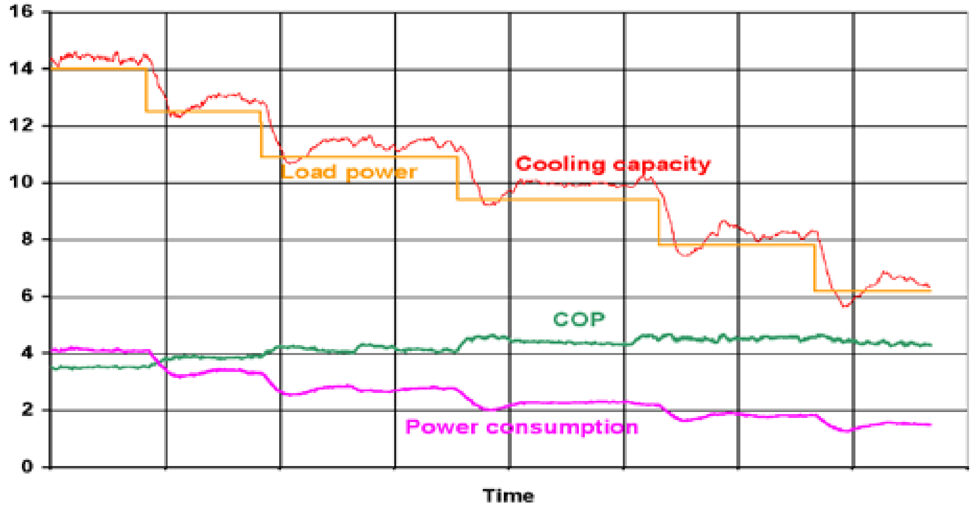


Fig. 2: Power consumption for inverter duty with maximum efficiency condenser control

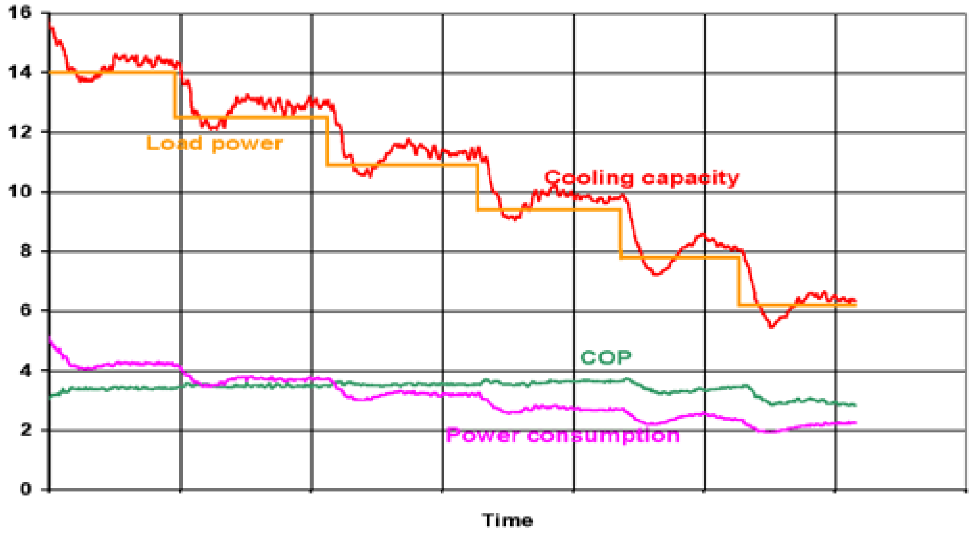


Fig. 3: Power consumption for inverter duty with constant condensing pressure control

Figures 4 and 5 show the pressures, superheat and refrigerant flow in both cases. We can also note how pressure drop on both sides decreases with the inverter frequency (four pressure transducers for each side, compressor outlet, condenser inlet and outlet, valve inlet for the high pressure side, valve outlet, evaporator inlet and outlet, compressor inlet for the low pressure side).

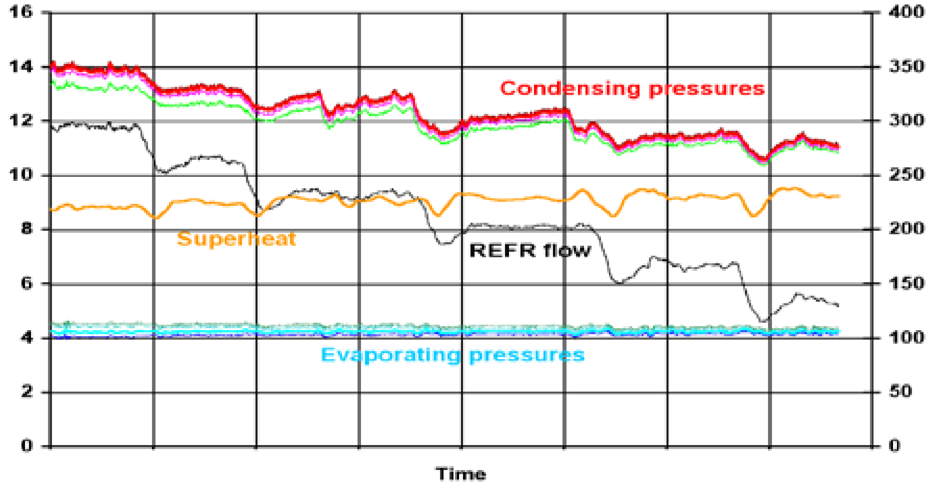


Fig. 4: Pressures and refrigerant flow for inverter duty with maximum condensing control efficiency

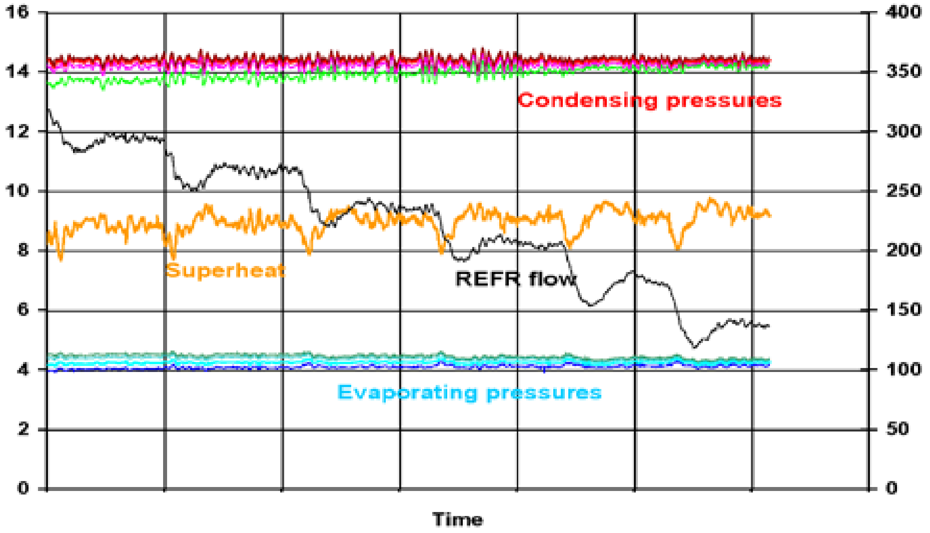


Fig. 5: Pressures and refrigerant flow for inverter duty with constant condensing pressure control

The final result in terms of unit COP is shown in Figure 6. As is clear, unit performance increases greatly lowering the load power with a maximum COP of 4.55 (at around 50% of load power).
The green line shows the maximum performance COP curve compared with the dark green one, which represents as explained the same inverter performance without the contribution of the lower condensing pressure control.

As a second result we found that unit COP has an evident decrease working around both maximum (75 Hz) and minimum (25 Hz) frequency due to the inverter power consumption and compressor design.
We think there will be no problems in total unit performance regarding a reduction in of COP at 75 Hz as this running frequency is definitely not frequent (estimated around 1...2% of total unit running time).
On the other hand it is possible to save energy by controlling the minimum inverter frequency in order to avoid the compressor working with very low COP.
For this reason the minimum inverter frequency has been calculated by the control algorithm on a case-by-case basis. It generally depends on the outside temperature and has been set between 30 and 35 Hz. We experienced that working with an ON/OFF modulating frequency stopped at the minimum value is sometimes more efficient than working at constant low frequency values.
(see Table 1).

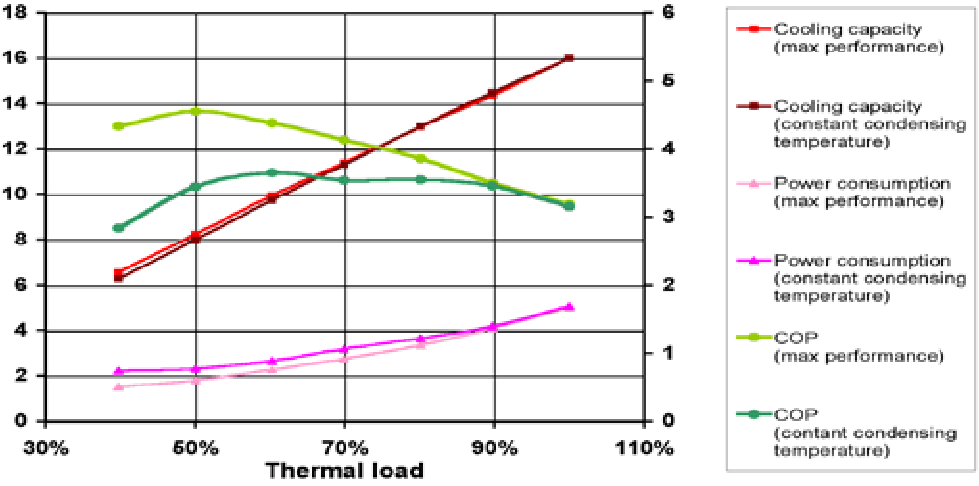


Fig. 6: Unit COP, power consumption and cooling capacity with maximum performance and with constant condensing pressure.

Comparative tests withtraditional ON/OFF duty

The main objective of the comparative tests is to measure the real influence of on-off duty on the power consumption of the chiller unit. Test specifications start with on-off duty at fixed 75 Hz inverter frequency regulating a variable heat load with a constant water set point (12 °C, 2 °C differential). Power consumption and temperatures were measured and average values were calculated in order to obtain water set point values for the inverter modulating frequency test: in this way we can measure mean power consumption with the exact same water temperatures and load in both unit duties. Figure 7 shows mean values of unit cooling efficiency (water temperature with a constant load power) and power consumption in both tests.

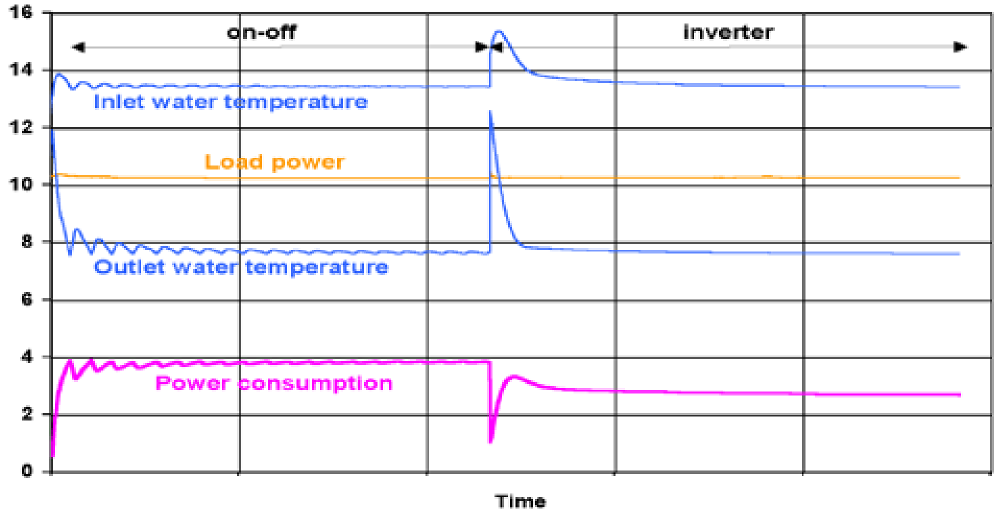
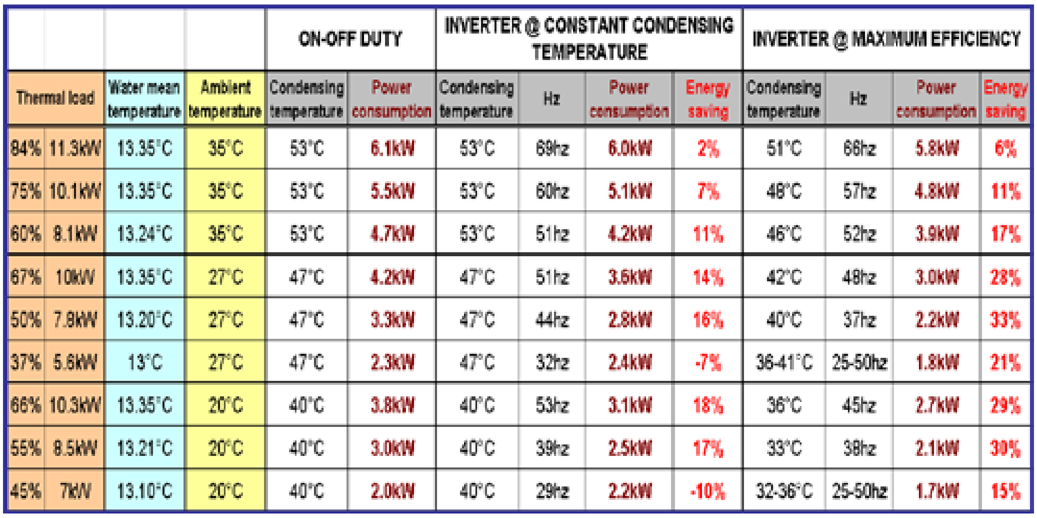


Fig. 7: Comparative test at 20 °C ambient temperature, 10.3 kW load power, around 70% of nominal load power.

Some of the comparative tests are summarized in Table 1.



				ON-OFF DUTY		INVERTER @ CONSTANT CONDENSING TEMPERATURE				INVERTER @ MAXIMUM EFFICIENCY			
Thermal load		Water mean temperature	Ambient temperature	Condensing temperature	Power consumption	Condensing temperature	Hz	Power consumption	Energy saving	Condensing temperature	Hz	Power consumption	Energy saving
84%	11.3kW	13.35°C	35°C	53°C	6.1kW	53°C	69hz	6.0kW	2%	51°C	66hz	5.8kW	6%
75%	10.1kW	13.35°C	35°C	53°C	5.5kW	53°C	60hz	5.1kW	7%	48°C	57hz	4.8kW	11%
60%	8.1kW	13.24°C	35°C	53°C	4.7kW	53°C	51hz	4.2kW	11%	46°C	52hz	3.9kW	17%
67%	10kW	13.35°C	27°C	47°C	4.2kW	47°C	51hz	3.6kW	14%	42°C	48hz	3.0kW	28%
50%	7.8kW	13.20°C	27°C	47°C	3.3kW	47°C	44hz	2.8kW	16%	40°C	37hz	2.2kW	33%
37%	5.6kW	13°C	27°C	47°C	2.3kW	47°C	32hz	2.4kW	-7%	36-41°C	25-50hz	1.8kW	21%
66%	10.3kW	13.35°C	20°C	40°C	3.8kW	40°C	53hz	3.1kW	18%	36°C	45hz	2.7kW	29%
55%	8.5kW	13.21°C	20°C	40°C	3.0kW	40°C	39hz	2.5kW	17%	33°C	38hz	2.1kW	30%
45%	7kW	13.10°C	20°C	40°C	2.0kW	40°C	29hz	2.2kW	-10%	32-36°C	25-50hz	1.7kW	15%

Tab. 1: Comparative test at various working conditions.

Both types of inverter control are listed and compared with ON/OFF duty in order to measure the exact increase in power consumption due to the inefficiency of on-off control and the better performance of inverter control at maximum efficiency (with lowest condensing temperature at each ambient temperature).

As already mentioned before (chap. 5) we experienced high power consumption at low inverter frequencies (below 35 Hz) due to the low COP of the compressor-inverter system when running at very low speed. Table 1 (line 4) shows a typical condition in which on-off duty is 7% more efficient than inverter duty and in which the inverter control works better by stopping the compressor at 25 Hz and starting it at around 50 Hz, with a modulation period in between.

Results and conclusion

Our main interest concerns control of the unit, first trying to achieve the best water stability and then the most effective reaction to all variations in load and ambient conditions. The main control algorithm with simple parameterisation has the possibility to achieve these results with all kinds of unit and inverter driven compressors, as the direct communication between inverter, valve and condenser control allows perfect “team work” in all conditions.

On the other hand, we found it necessary to create a map of the unit, especially concerning inverter and compressor efficiencies, in order to keep working conditions always in a good performance range. For this reason, there may be cases in which the control algorithm prevents the unit from working at low or high inverter frequencies, or decreases the unit cooling capacity to maximize unit COP.
As far as the comparative tests are concerned, we established a test protocol to measure the real influence of the on-off duty on the unit COP, which results in an higher power consumption, up to 15%, depending on load power. As a second step we considered that a unit working at lower frequencies is definitely oversized compared to nominal conditions: this allows us to achieve get better efficiencies by lowering condensing pressure, with up to 30% less power consumption at medium range inverter frequencies.

It is clear that all power consumption data include the consumption of the inverter itself: when comparing with an ON/OFF standard compressor we have to reduce the power saving results.
On the other hand, a standard compressor (50 Hz, 380 V) is more expensive than a smaller inverter driven compressor that can work at up to 75 Hz with the same cooling capacity.

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