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An Integrated Solution for Commercial AC Chillers Using Variable Speed Scroll Compressors

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ABSTRACT

For a couple of years already, variable speed compressor technology has become a standard for residential heating and cooling applications. Indeed, as a response to increasing performance requirements, small capacity variable speed scroll compressors optimized for heating and cooling applications were released and progressively adopted on the market.

In January 2018, the first tier of the Ecodesign Directive (2009/125/EC) requirements defined for commercial AC chillers will enter into force across European Union. The application of this new regulation will most likely drive the European commercial AC market toward a similar direction than the residential market and a more intensive adoption of the variable speed technology, especially for systems below 400kW rating cooling capacity.

This paper presents integrated solutions targeting efficient implementation of variable speed technology in commercial water chillers, allowing system manufacturers to face new regulatory challenges.

The considered solution integrates multiple configurations of variable speed and fixed speed scroll compressors, variable frequency drive, electronic expansion valve and control. Compressors envelopes management and protection as well as superheat control capabilities are presented.

Seasonal performance simulations have been realized according to EN14825 to quantify the gain of variable speed technology.

Laboratory testing has been performed to develop and qualify the considered solution. Testing on a real Air-to-Water chiller has also been realized to fine-tune the control and measure the achieved efficiency levels.

1. INTRODUCTION

Until today, no regulation imposes minimal energy performance requirements (MEPS) for chillers on the European market. Only nominal rating performance in cooling (Energy Efficiency Ratio – EER) and heating (Coefficient Of Performance – COP) had to be measured according to EN14511 and published. Seasonal performance in cooling mode was also often indicated by manufacturers in the form of Eurovent's ESEER certified value, but only on voluntary basis.

Since January 2015, minimal seasonal performance requirements are in application for heating systems (including residential and commercial heat pumps, up to 400 kW rating capacity) as defined in the Lot 1 of Energy-related Products (ErP) Ecodesign Directive (2009/125/EC). European energy labels, intended to inform end-users, have also to be provided for systems below 70kW rating capacity. In January 2018, a similar regulation for AC systems will entry into force and the first tier of the requirements defined for chillers will be in application across European Union.

This new regulation provides also the methodology and reference normative by which obtaining the seasonal primary energy efficiency, η % value, which is directly related to the seasonal efficiency ratio (SEER) defined in EN14825.

It is anticipated that the entry into force of this regulation, as well as other regulatory aspects (such as Energy Performance of Buildings Directive and European F-Gas Regulation aiming at reducing the environmental impact of high GWP refrigerants) and technology trends, will have very significant and very different impacts on the market and the design of chillers of rating cooling capacity below and above 400kW.

The first part of this paper includes a description of upcoming performance regulation impacting the European commercial AC market. General principles of the testing and calculation method, based on EN14825, used to measure seasonal performance of chillers are presented. In the second part of the paper, the development of integrated solutions for efficient implementation and operation of Variable speed technology in commercial chillers is described. Conducted experimental and modeling activities are also introduced.

2. SEASONAL ENERGY PERFORMANCE REQUIREMENTS

The upcoming European Commission Regulation setting minimal performance requirements for cooling products is being established in the frame of implementation of ErP directive, and being currently finalized. Minimal requirements are defined in terms of seasonal primary energy efficiency and can be converted into seasonal energy efficiency ratio (SEER) values, as shown in Table 1 for space cooling water chillers.

Table 1: Minimal seasonal performance requirements for space cooling chillers

		Tier 1 Jan 2018	**Tier 2 Jan 2021**
A/W	<400 kW	3.80	4.10
	≥400 kW	4.10	4.55
W/W	<400 kW	4.98	5.08
	≥400 kW and <1500 kW	5.75	6.38
	≥1500 kW	6.20	6.88

While first tier of requirements is achievable with today technology, it is expected that tier 2 will require significant redesign of existing chiller systems available on the market.

2.1 Seasonal Performance of Systems

The methodology defined in EN14825 to establish the seasonal performance index of chillers can be defined in three successive steps:

1. Unit performance measurement at 4 reference test conditions
2. Performance interpolation across standard European cooling season to establish active mode performance
3. Calculation of seasonal energy efficiency ratio (SEER)

First the steady-state performance (declared capacity and energy efficiency ratio) of the full unit (including compressors, air and water side auxiliaries and controls) has to be measured at 4 reference conditions (Table 2) representing different full load and part load regimes and operating conditions (ambient and water temperatures). Three water temperature regimes are considered for fan coil applications (12/7°C) with fixed or variable outlet setpoint and cooling floor application (23/18).

Table 2: Reference conditions for Air-to-Water chillers

Rating Point	Ambient Temperature (°C)	Part Load Ratio (%)	Fan Coil inlet/outlet water temperature (°C)		Cooling Floor inlet/outlet water temperature (°C)
			Fixed outlet	Variable outlet	
A	35	100	12/7	12/7	23/18
B	30	74	*/7	*/8.5	*/18
C	25	47	*/7	*/10	*/18
D	20	21	*/7	*/11.5	*/18

In part load regime (conditions B, C and D), impact of ON-OFF cycling of the unit (i.e. between smallest capacity stage and zero) has to be integrated according to equation (1) and may end in severe degradation of the declared performance (EERd), depending on the capacity ratio (CR) and degradation coefficient (CC).

$$EER_{PL} = EER_d * \frac{CR}{CC*CR+1-CC} \tag{1}$$

For example, assuming a capacity ratio (CR) of 50% between cooling demand and unit capacity at a given condition and a degradation factor (CC) of 0.9, EER degradation reaches 9.1%. Then, a steady state EERd of 4 in operation would actually be recognized as 3.6 in part load (EERpl) by the method. EN14825 provides the method to establish the actual value of the cycling degradation coefficient. If this test has not been performed, a default value of 0.9 should be applied.

In case of ON-OFF cycling of the unit, water temperature set point has also to be lowered to take into account outlet temperatures variations. This correction further impacts performance of the unit since evaporating temperature is changing accordingly.

In a second time, measured full load and part load performance at A, B, C and D conditions are interpolated in order to establish the active seasonal performance, $SEER_{ON}$. The calculation method includes finding an EERpl value for each temperature bin within the temperature interval of the climate zone. Interpolated values are used for temperatures between the determined reference test points. For temperatures outside the test points, closest measured values are used.

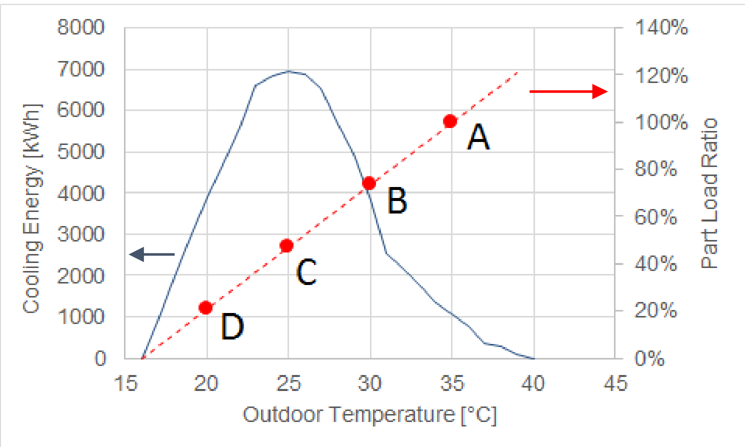

Figure 1: Cooling Energy & Part Load curves for a 80kW unit

Since significant number of operating hours occur at medium-low ambient (and cooling load), part load performance of the unit is crucial in order to achieve high overall seasonal performance. On the contrary, only limited number of hours are considered for full load operation (Figure 1).

Finally, unit energy consumption during auxiliary modes has to be integrated to deduce the reference SEER which is the ratio between the reference annual cooling demand (in kWh) and the annual energy consumption (Equation 2). The annual electricity consumption (Equation 3) includes thermostat off mode, standby mode, crankcase heater mode, and off mode; each mode corresponding to a particular power consumption (P) and a number of running hours defined in the regulation (H).

$$SEER = \frac{Q_C}{Q_{CE}} \qquad (2)$$

$$Q_{CE} = \frac{Q_C}{SEER_{ON}} + H_{TO} * P_{TO} + H_{SB} * P_{SB} + H_{CK} * P_{CK} + H_{OFF} * P_{OFF} \qquad (3)$$

Of course, auxiliary modes have also a considerable impact on final seasonal performance and particular attention has to be paid to reduce energy consumption in such modes to the minimum.

2.2 Seasonal Performance Simulations

A simulation tool has been developed internally to allow seasonal performance calculations on non-reversible and reversible chiller systems according to the related standard. To allow system seasonal performance simulation, the calculation tool has to integrate, not only compressors performance data, but also heat exchangers performance and auxiliaries consumptions (fans, pumps, crankcase heaters...).

Simulations of an R410a Air-To-Water chiller have been carried out to compare different compressors configurations and technologies. Assumptions regarding heat exchangers have been defined to reflect state-of-the-art chiller technology:

- Evaporator plate heat exchanger approach of 3K in nominal full load operation (Water inlet/outlet temperatures: 12/7°C and evaporating temperature of 4°C)
- Fin-and-tube condenser coil with an approach of 15K in nominal full load condition (35°C outdoor temperature and 50°C condensing temperature)

In a single compressor systems, cycling losses are critical. For a single fixed speed compressor, compressor “gross” EER is progressively degraded due to system auxiliaries (EERnet) and then due to cycling losses (EERpl). Of course, cycling losses become significant at low load (low capacity ratio), leading to a degradation of the unit EER up to 70% (Figure 2). Part of this performance degradation is due to water setpoint correction which can reach 3 to 4 K.

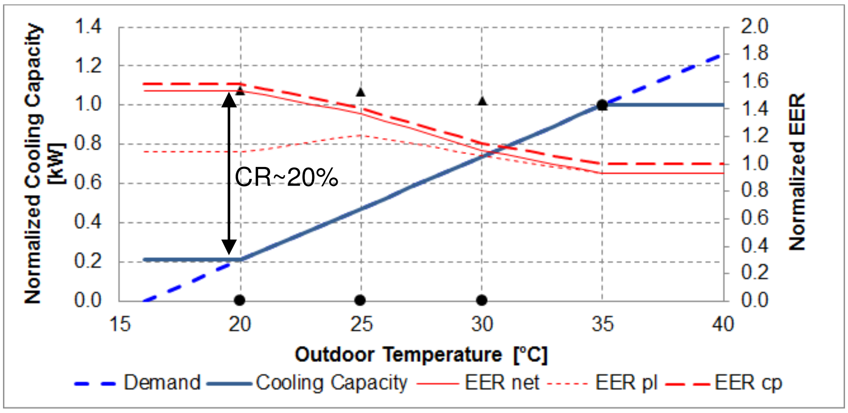

Figure 2: Cooling Load & EER Curves For Fixed Capacity Compressor System.

When properly designed and used, variable speed technology allows to cover most of the capacity demand without any ON-OFF cycling. EER degradation is then mainly due to water-side and air-side auxiliaries (Figure 3). Overall seasonal performance gain comparing to a fixed speed system may reach 15 to 20%.

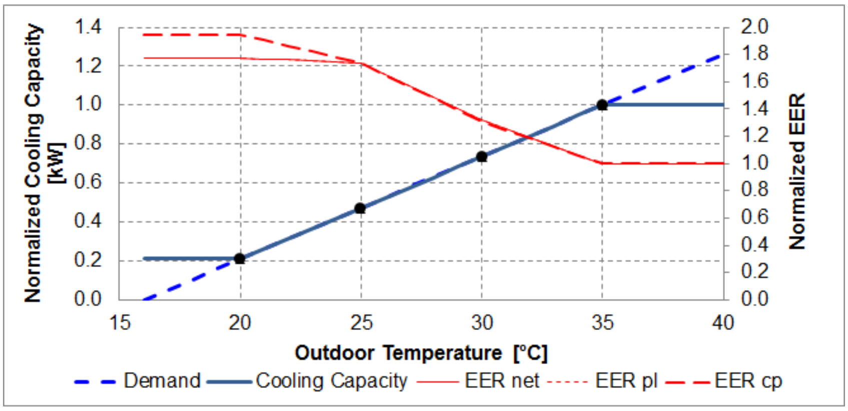

Figure 3: Cooling Load & EER Curves for Variable Speed Compressor System.

While variable speed brings significant performance gain for small and medium-size systems, in larger systems with multiple fixed capacity compressors (ex: dual-circuit unit with one tandem of compressors per circuit), gain is relatively limited and typically reaches a few percent (Table 3). Indeed, in such configurations, the presence of multiple capacity stages allows strongly reducing the impact of cycling losses.

Table 3: Normalized Seasonal Performance for Various A/W Chiller Configurations

System Configuration	Number of Refrigerant Circuits	Number of Compressors	Normalized SEER
Fixed Capacity Compressor	1	1	100% (Reference)
Variable Speed Compressor	1	1	117%
Fixed Capacity Tandem	1	2	113%
Variable Speed Tandem	1	2	119%
2 x Fixed Capacity Tandem	2	4	121%
2 x Variable Speed Tandem	2	4	122%
2 x Fixed Capacity Trio	2	6	122%
2 x Variable Speed Trio	2	6	122%

As already mentioned, power consumptions of auxiliaries (pumps, crankcase heaters…) also have a negative impact on overall seasonal performance of the systems, of about 6 to 7% in average.

Medium and large chillers (250 kW rating cooling capacity and above) often embark multiple compressors and can continue to rely on proven and efficient fixed speed compressors, used in tandem or trio on one circuit or more. However, design of smaller systems usually using one or two compressors will have to be adapted and integrate variable speed technology.

3. INTEGRATED SOLUTION FOR SYSTEMS USING VARIABLE SPEED SCROLL COMPRESSORS

3.1 Variable Speed Scroll Technology

In 2012, cooling optimized and heating optimized high efficiency variable speed scroll compressors have been released and we very successful on European residential heat pump market, covering a range from 4kW to 23kW rating capacity. Those compressors are qualified with R410A refrigerant and are controlled by an Emerson drive (Dardenne et al., 2014). In 2013, an integrated "Refrigerant Module for Heating" (RMH) has been developed using this technology. This is a refrigerant circuit designed for use in split air-to-water heat pump applications, where the evaporator is located outdoors. RMH integrates the aforementioned vapor injection variable speed compressor, its drive, the indoor refrigerant circuit (i.e. economizer, liquid receiver…) and its "Refrigerant Circuit Controller" (RCC).

In 2014, the existing range of variable speed compressors has been extended with larger capacity variable speed scroll compressors, dedicated to commercial AC market. This last generation of variable speed scroll compressors provides the following advantages

- Expanded operating envelope providing great flexibility in design of reversible systems
- Expansive 900-7200 RPM speed range for enhanced light load efficiency
- Optimized scroll elements for variable speed performance and efficiency boost in part load operation
- Low oil circulation compressor plus scroll oil injection for low speed performance and reliability
- Permanent magnet motor technology for highest efficiency
- Capability to build tandems and trios with fixed speed compressors for maximum flexibility in system design

These compressors were not released alone but were integrated with the range of fixed speed compressors, allowing proposing multiple combinations (tandem and trio combinations of fixed and variable speed compressors) to cover various needs and capacities. Paralleling of variable speed scroll compressors has been made possible by paying particular attention to oil balancing and piping robustness (Figure 4).

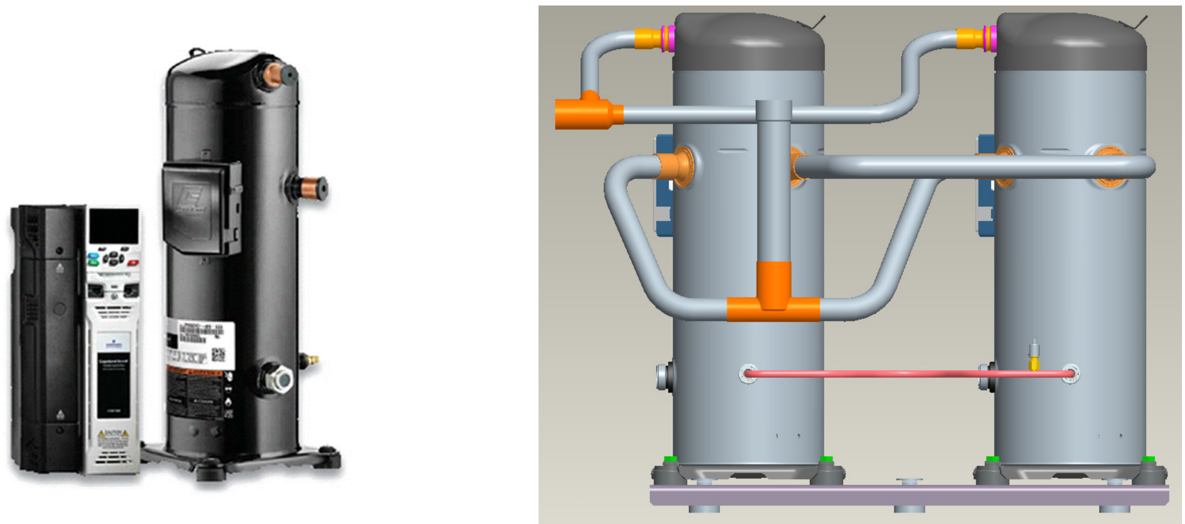

Figure 4: 15hp Variable Speed Scroll Compressor & Inverter Drive (left). Fixed & Variable Speed Scroll Compressors Tandem (right)

Variable speed scroll technology brings also many other advantages, such as: enhanced control accuracy, continuous capacity management, reduced startup current, low sound emissions at part load and during cycle reverse transitions of reversible systems.

Compressor-drive matching is also critical and requires particular attention in order to deliver the best performance in terms of motor and inverter drive efficiency and reliability. Active protection algorithms incorporated into the motor control drive safeguard the compressor and drive from many adverse operating conditions, including:

- Motor & scroll temperature protection
- Locked rotor detection
- Phase protection and correction
- Maximum operating current detection
- Anti-short cycling

3.2 Integrated Solution for Reversible Chillers

Implementation of variable speed technology in chiller systems also represent a significant challenge for system manufacturers, in terms of system design, control and qualification. For that reason, some integrated solutions have been developed to:

- Allow easier and effective implementation of variable speed technology in systems by proposing pre-qualified sets of optimized components (compressors, drive, expansion valve and controls), ready for assembly, to system manufacturers
- Increase performance of systems, not only through the use of variable speed technology, but also through more efficient system control and management in steady-state and transient operation
- Reach maximal reliability by integrating active protection and fault detection capabilities

Typically, the integrated solution includes (Figure 5):
- the fixed and a variable speed scroll compressors (up to three per circuit), installed in tandem or trio,
- the inverter drive with Modbus communication capability
- the bipolar stepper motor electronic expansion valve
- the pressure transducers and temperature sensors
- the circuit controller, managing the main components of the refrigerant circuit

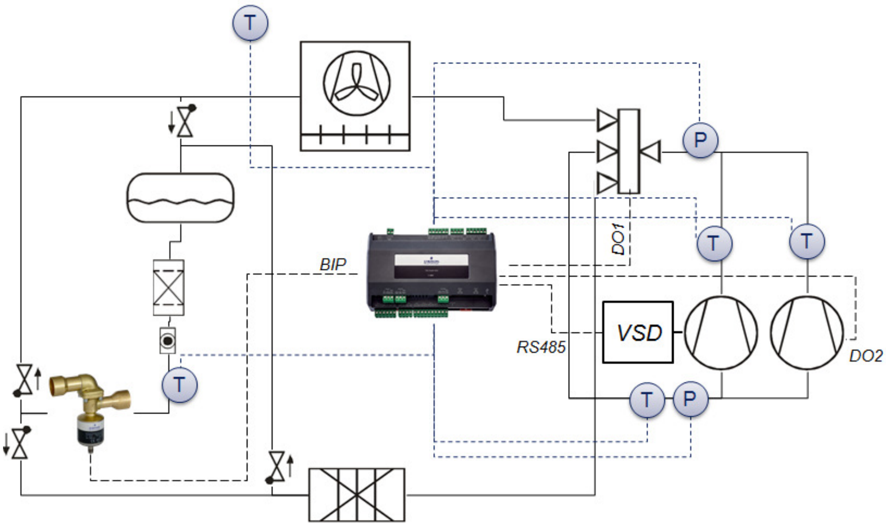

Figure 5: Typical arrangement of the main elements of the integrated solution for a fixed & variable speed scroll compressors tandem chiller

The peculiarity of the solution resides in the parallel management of compressors and electronic expansion valve. The control uses predictive algorithms relying on compressors and valve performance mapping data allows achieving more accurate and dynamic control of the system as well as active protection of the system.

The circuit control ensures variable speed compressor envelope management and drives the compressor in a smooth way across the different regions of its operating envelope (Figure 6). The fixed speed compressor is also driven (i.e. started or stopped) by the circuit controller according to the capacity request provided by the unit or plant controller.

In parallel, the electronic expansion valve (EEV) is driven to maintain compressors suction state within acceptable range to ensure efficient and reliable operation, avoiding too high superheat (typically >20K) or liquid floodback. EEV control during transient is crucial and has to match fast systems capacity variations (speed ramp-up/ramp-down and fixed speed compressor cycling) and transitions (cycle reversing for defrost or cooling/heating modes transitions, oil recovery cycles). To this end, smart control logics, including fuzzy logic, adaptive PID and dynamic valve prepositioning, have been implemented.

EEV control is critical to ensure optimal system efficiency in steady-state operation. Indeed, too high superheat may quickly lead to inefficient operation due to excessive approach temperature in evaporator plate heat exchanger, leading to lower evaporating temperature levels and higher compressor power consumption. While lowering evaporator superheat is beneficial for system overall performance, it also increases the risk of liquid floodback to the compressor. Then, smart control algorithms relying on compressor and valve performance mapping equations are used to increase control robustness and achieve optimal superheat levels, below standard 5K thresholds, in a safe and reliable way.

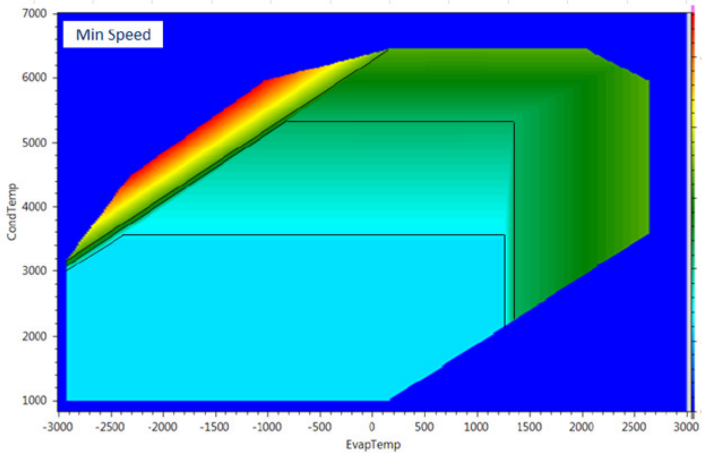

Figure 6: Variable Speed Compressor Envelope with Different Speed Regions

Of course, integrating compressors and EEV control can bring significant advantages in terms of active compressor protection, such as anticipation of high/low evaporating or high condensing limits crossing or floodback and activation of adapted corrective actions (compressor speed or valve opening adjustment)

4. SOLUTION PROTOTYPING AND TESTING

To validate and fine-tune the advanced control and protection logics embedded in the circuit controller, the whole solution (compressors, drive, valve, sensors and controllers) were implemented in a real-life environment. A commercial reversible A/W chiller (Figure 7) has been installed and connected to an existing process cooling glycol loop (maintained at approx. 15°C all year long by several large A/W chillers).

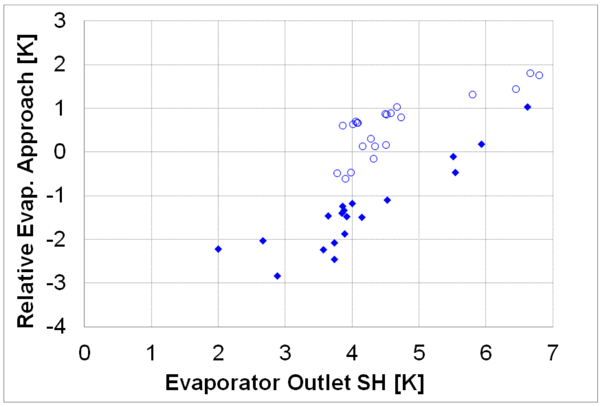

Figure 7: A/W Chiller Equipped with Variable Speed Scroll Solution (left) and test results (right)

The 2-circuits unit, originally equipped with two tandems of fixed speed compressors has been modified. Compressors have been replaced by new generation variable and fixed speed scroll compressors. A new EEV has also been installed.

Both steady-state and transient tests were performed between July and November 2015, mainly in cooling operation. During the test, the gain of low superheat control on evaporator approach, and then, on system performance was highlighted (Figure 7) especially at part load. Seasonal performance gain vs standard superheat control was estimated to 5 to 6%.

6. CONCLUSIONS

European systems manufacturers are facing challenging times. New regulations are strongly impacting the commercial AC business and the design of new chiller systems.

To meet upcoming minimal seasonal performance requirements, light commercial systems (below 250 kW rating cooling capacity) are likely to widely adopt variable speed compressor technology as residential AC and heat pump market did a few years ago.

Implementation of variable speed technology in chiller systems will allow significant performance gain comparing to standard design but also represents a significant challenge for system manufacturers, in terms of system design, control and qualification.

To support system manufacturers and allow them developing efficient and reliable systems with variable speed scroll technology, an integrated solution was developed, comprising a range of fixed speed and variable speed compressors able to work in tandem/trio configurations, inverter drives, electronic expansion valves and corresponding sensors and controls. The complete solution was implemented, tested and validated on a real A/W chiller.

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