Efficient Management of HVAC Systems

Mirco Rampazzo

Università degli Studi di Padova
Dipartimento di Ingegneria dell'Informazione

Dottorato di Ricerca in Scienza e Tecnologia dell'Informazione
XXII Ciclo

Direttore della scuola: Ch.mo Prof. M. Bertocco
Supervisore: Ch.mo Prof. A. Beghi

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Outline

1 Motivation
- HVAC Systems
- Multiple-chiller systems

2 Implementation and main results
- Models, Control and Optimization
- Examples

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1. Motivation
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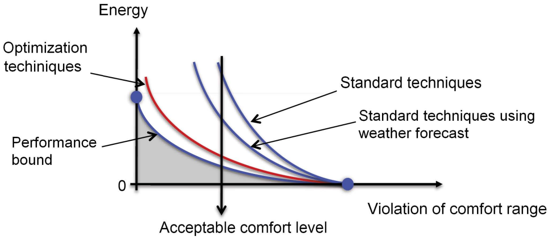
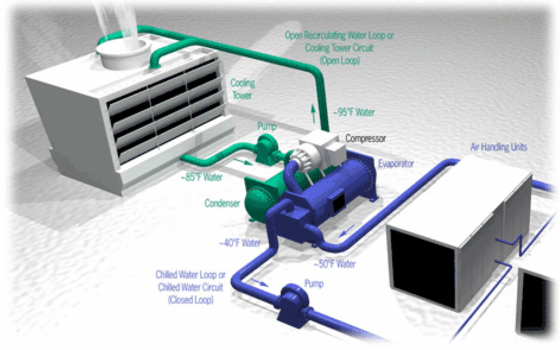
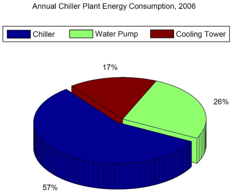
Heating, Ventilation and Air-Conditioning System

- Heating, Ventilation and Air Conditioning Systems (HVAC) represents one of the most complex challenges for control and optimization.
- It comes as no surprise that much of HVAC control and optimization is about compromise: a balance that usually results in reasonable comfort at minimum energy use and financial costs.



Heating, Ventilation and Air-Conditioning System





- Chillers are a key component of air conditioning systems for large buildings. They produce cold water to remove heat from the air in the building.
- In HVAC system equipped with chillers, the electrical energy consumption of the refrigerating units far exceeds all that required by the other system components.

Screw and Scroll Chiller

Screw compressor

- a pair of helical rotors are used;
- the volume of interlobe space decreases and refrigerant is compressed;
- less moving parts.
- lower maintenance and longer life spans.

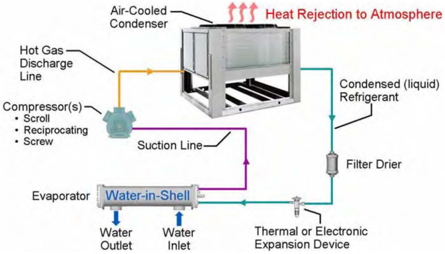
Scroll compressor

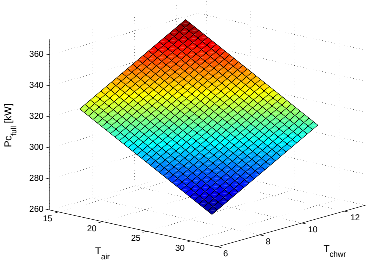
- refrigerant is compressed by two offset spiral disks (nested together);
- smooth-operating units;
- high efficency compression ratio;
- high efficiency at part load.

Screw compressor

Scroll compressor

Energy analysis of air condensed chiller





Electric power consumption and cooling power (continuous working at full capacity)

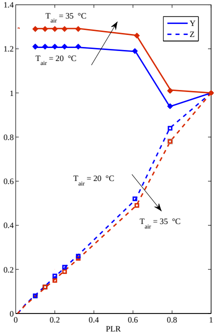
$$P_{e_{full}}(t) = a_e + b_e T_{chwr}(t) + c_e T_{air}(t) + d_e \dot{m}_w(t) + e_e T_{chwr}(t)\dot{m}_w(t)\,. \tag{1}$$

$$P_{c_{full}}(t) = a_c + b_c T_{chwr}(t) + c_c T_{air}(t) + d_c \dot{m}_w(t) + e_c T_{chwr}(t)\dot{m}_w(t)\,. \tag{2}$$

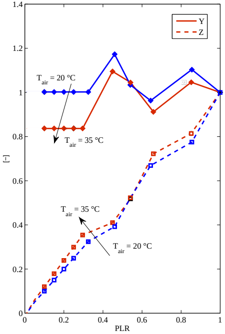
$$EER_{full} = \frac{P_{c,full}}{P_{e,full}}\,. \tag{3}$$

Energy analysis of air condensed chiller

In order to carry out a correct energy analysis an evaluation of the effect of operating at part load conditions is required.



(a) TCAE 4320, scroll unit.



(b) TCAVBZ 2600, screw unit.

Penalty curves

$$PLR_{cyc} = \frac{P_{c,cyc}}{P_{c,full}}. \tag{4}$$

$$EER_{cyc} = \frac{P_{c,cyc}}{P_{e,full}}. \tag{5}$$

$$Z = \frac{P_{e,cyc}}{P_{e,full}}. \tag{6}$$

$$Y = \frac{EER_{cyc}}{EER_{full}}. \tag{7}$$

$$P_{c,cyc} = PLR_{cyc} \cdot P_{c,full}. \tag{8}$$

$$P_{e,cyc} = Z \cdot P_{e,full}. \tag{9}$$

- Remark: the influence of the external air temperature is not negligible!

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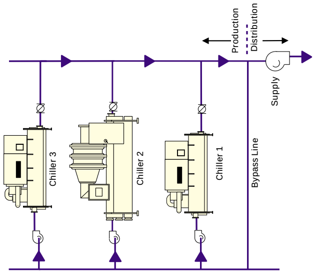
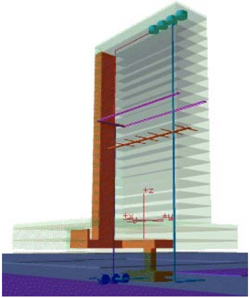
Multiple-chiller systems





Every chiller is independent of each other to provide:

- standby capacity;
- operational flexibility;
- less disruption maintenance.

Compared with a single-chiller system it has:

- a reduced starting in-rush current;
- reduced power consumption under part load conditions.

Candidates for this type of solution are HVAC plants of medium-high cooling capacity, for instance:

- institutional and directional facilities;
- health-care.

Remark

- The problem of efficiently managing multiple chiller systems is complex in many respects.

Optimal Chiller Operations

Optimal Chiller Loading (OCL)

The OCL problem is to find a set of chiller output which does not violate the operating limits while maximizing the EER and keeping the cooling demand satisfied (i.e. the sum of cooling load of each chiller, Q_i, have to satisfy the system cooling load Q_{CL}). The constrained maximization problem results:

$$\arg\max_{PLR_i} \sum_i EER_i \,, \tag{10}$$

subjected to:

$$\sum_i Q_i = Q_{CL} \,, \tag{11}$$

where $i \in \{1, ..., n_{ch}\}$ and n_{ch} is number of chillers.

Optimal Chiller Operations

Optimal Chiller Sequencing (OCS)

The OCS problem consists in determining which of the chillers should be on-line and off-line, while minimizing the input power and satisfying the chiller operational constraints.

$$\arg \min_{status_i} \sum_t \sum_i InputPower_i \,, \qquad status_i \in \{on, off\} \tag{12}$$

subjected to:

- Cooling load balance equation:

$$\sum_i Q_i = Q_{CL} \,. \tag{13}$$

- Loading limit:

$$PLR_{min,i} \leq PLR_i \leq PLR_{Max,i} \,. \tag{14}$$

- Minimal Up Time (MUT) and Minimal Down Time (MDT) constraints:

$$MUT_i \geq MUT_{min,i} \,, \tag{15}$$

$$MDT_i \geq MDT_{min,i} \,. \tag{16}$$

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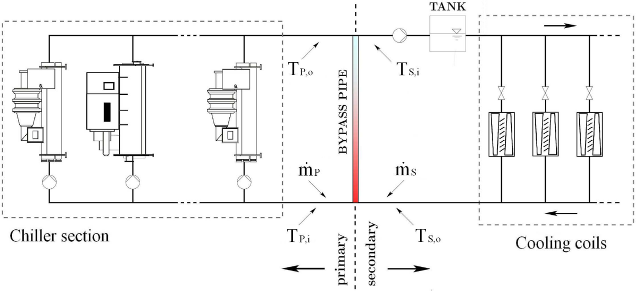
System Structure

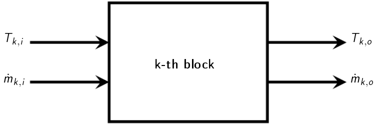
The hydronic basic system:



1. The energy production section: a packaged air-cooled water chiller.
2. The hydraulic section: a common primary-secondary pumping arrangement is adopted with constant water flow rate on the secondary.
3. The load section.

Mathematical Model

- The thermal behavior: analyzed by a lumped formulation.
- The elements of the plant are simulated through blocks, the heat transfer processes are considered as concentrated inside the blocks.
- The mass and energy equations are implemented as block equations for each component of the plant; each block is modelled as a thermodynamic open system.



- **The fluid flow problem.**

$$\dot{m}_{k,i} - \dot{m}_{k,o} = 0 \, . \tag{17}$$

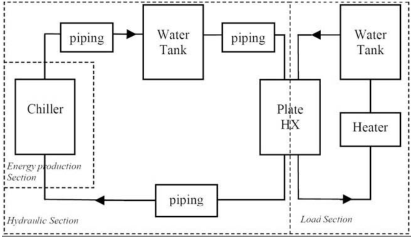
- **The thermal problem:**

$$\begin{aligned} \frac{dQ_k}{d\tau} - \frac{L_k}{d\tau} &= -\dot{m}_{k,i}\left(c_p T_{k,i} + e_{p,k,i} + e_{c,k,i}\right) \\ &\quad + \dot{m}_{k,o}\left(c_p T_{k,o} + e_{p,k,o} + e_{c,k,o}\right) \qquad (18) \\ &\quad + \frac{\partial}{\partial \tau}\int_0^{V_k} e\rho dv \, . \end{aligned}$$

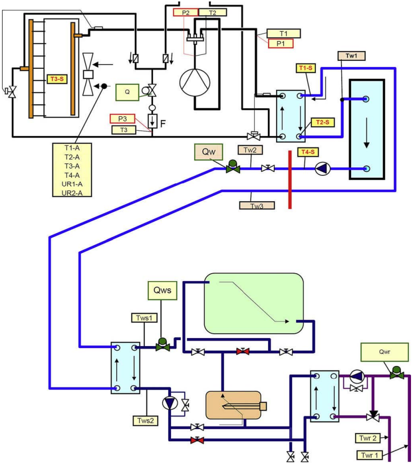
The blocks:

- Chiller.
- Cooling coil.
- Pipe.
- Water storage tank.
- Bypass line.
- Collector.

Model Validation



- Energy production section: Rhoss TCAEY 130 (29.1 kW, single scroll compressor).
- The hydraulic section: 45 l water tank, piping total volume 36 l.
- Pump constant water flow rate: 1.28 kg/s.
- Brazed plate heat exchanger (BHE).
- Water tank: 480 l.
- Load section: electrical heater (0-50 kW).

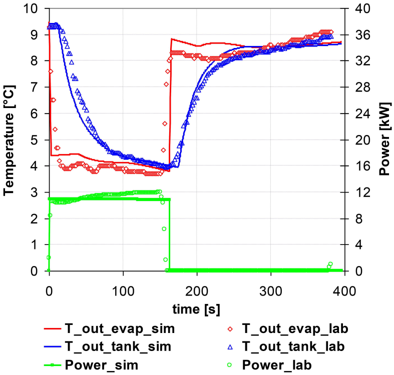


P&ID diagram

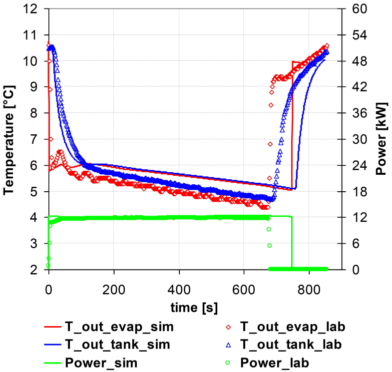
Model Validation

The model is fully adequate for reproducing the main dynamic behaviors that are relevant for controller design.

- Comparison between experimental and virtual system at 20% part load ratio.

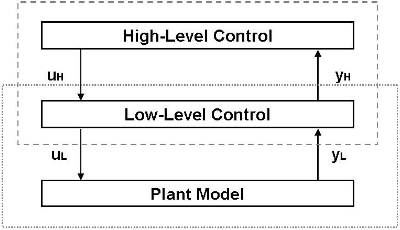


- Comparison between experimental and virtual system at 75% part load ratio.



Two Level Control

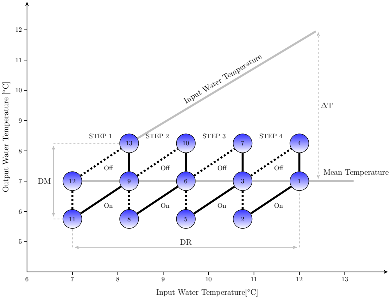
Two-level control structure is used:



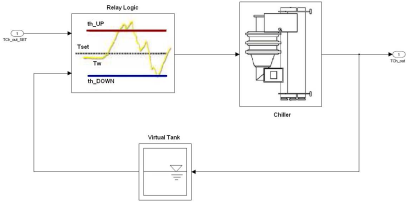
- The low-level local loop control of a single set point is provided by an actuator (with a relay logic).
- The upper control level, supervisory control, specifies set points and other time-dependent modes of operation.

Low Level Control

- Chillers evaporator water outlet control is adopted. It grants better performance during chiller part load operations.



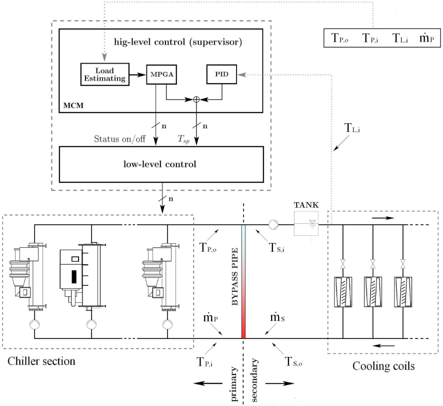
- Relay logic with virtual tank is employed. It increases the inertia seen by the chiller controller.



High-Level Control

The Multi-Chiller Management (MCM) consists of three main components

1. a load estimation algorithm;
2. a Multi-Phase genetic algorithm for solving the OCL and OCS problems;
3. a PID controller.



Problem formulation

Optimization

- The aim of the optimization problem is to minimize chillers energy consumption keeping the cooling demand satisfied.
- In order to minimize the input electric power and satisfy the chiller operating constraints, at each supervision period, OCL and OCS problems are solved.

For each chiller are given:

- the status: on-line or off-line;
- the fraction of the total cooling load to be supplied;
- the water outlet set-point temperature.

Problem formulation

Constrained minimization problem

$$\arg\min_{(PLR_i,\ status_i)} \sum_i E_i \ , \tag{19}$$

$$\sum_i Q_i = \hat{Q}_e = \hat{P}_L \cdot \Delta\tau \ , \tag{20}$$

$$\left| PLR_i - PLR_{i_{prev}} \right| \leqq \kappa_i \ . \tag{21}$$

$$\dots \tag{22}$$

⇓

Unconstrained minimization problem

$$\arg\min_{(PLR_i,\ status_i)} OBJ \ , \qquad i = 1, \dots, n \ ; \tag{23}$$

$$OBJ \triangleq h_{obj} \left[\sum_i E_i \right]^{\nu_{obj}} + h_{err} \left| \sum_i Q_i - \hat{Q}_e \right|^{\nu_{err}} + h_{reg} \left[\sum_i \max\left(0,\ \left| PLR_i - PLR_{i_{prev}} \right| - \kappa_i \right) \right]^{\nu_{reg}} + \dots \tag{24}$$

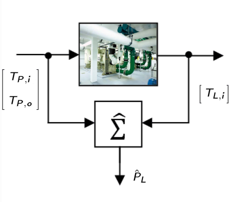
Load Estimation

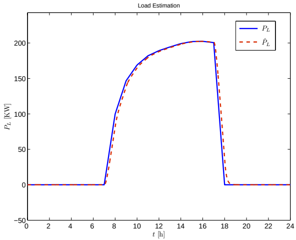
- At each supervision period knowledge of the total cooling demand is needed.
- The load is assumed to be slowly varying.
- The information available: the inlet and supply water temperatures and water flow rate in primary section.

On the basis of state space model (25), a standard Luenberger observer is designed in order to obtain the estimated load $\hat{P}_L$.

$$\begin{cases} P_L(n+1) = P_L(n) \\ T_{L,i}(n+1) = \dfrac{\mathcal{T}_s}{\rho c_p V_{tank}} P_L(n) + T_{L,i}(n) + \dfrac{\dot{m}_P \mathcal{T}_s}{\rho V_{tank}} T_{P,o} - \dfrac{\dot{m}_P \mathcal{T}_s}{\rho V_{tank}} T_{P,i} \end{cases} \tag{25}$$

Load Estimation Scheme

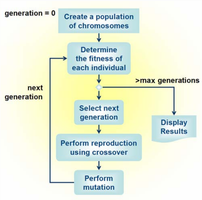




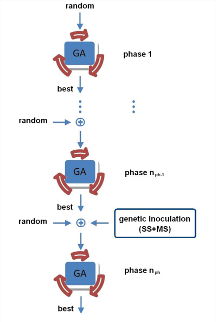
Multi-Phase Genetic Algorithm (MPGA)

- Conventional GAs suffer from bad initializations.
- A Multi-Phase GA method is proposed.
- Inoculation (a way to incorporate such knowledge).

GA



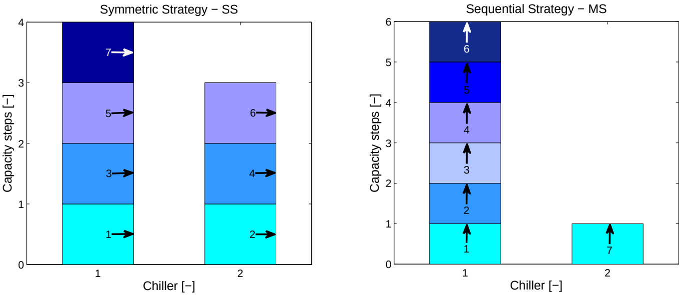
MPGA



MPGA

Common strategies for a set of n-parallel chillers with m-discrete capacity steps system

- Symmetric Strategy (SS).
- Sequential Strategy (MS).



MPGA

Chromosome example: PLR and status of n chillers are encoded into a binary string of (10+1)n bits.

$PLR_{1(1)}$	…	$PLR_{1(10)}$	status$_1$	…	$PLR_{n(1)}$	…	$PLR_{n(10)}$	status$_n$

MPGA control parameters

Portions of individuals

$$\text{phase } j_{ph} = 1 \ldots n_{ph} - 1 \qquad \begin{cases} L & \text{best of previous phase} \\ (1-L) & \text{random} \end{cases}$$

$$\text{phase } j_{ph} = n_{ph} \qquad \begin{cases} L & \text{best of previous phase} \\ (1-L) & \begin{cases} (1-L)L_1 & \begin{cases} (1-L)L_1 L_2 & \text{SS} \\ (1-L)L_1(1-L_2) & \text{MS} \end{cases} \\ (1-L)(1-L_1) & \text{random} \end{cases} \end{cases}$$

Population size	100	Mixing factor L_1	0.5
Generation number	500	Mixing factor L_2	0.5
String length	11	h_{obj}	10÷20
n_{ph}	5	ν_{obj}	1
n_{g}/ph	100	h_{err}	5÷10
Crossover probability	0.6	ν_{err}	2
Mutation probability	0.03	h_{reg}	(1÷5)e4
Selection method	*rws*	ν_{reg}	1
Mixing factor L	0.5	k_i	0.2÷0.5

Chiller water outlet set-point temperature

MPGA

- From best PLR_i and $status_i$, the set-point $T_{sp_i GA}$, for the i-th chiller can be estimated as:

$$T_{sp_i GA} = T_{P,o} + \left(\hat{PLR}_{Tot} - PLR_i \right) \Delta T_{oi}. \tag{26}$$

PID

- The PID controller job is to maintain the inlet load-side water temperature at a certain level so that the error ($e_{T_{sp}}$), between the process variable and the set-point, is bounded. The chiller set-points are modified by:

$$T_{sp_i} = T_{sp_i GA} + K_p e_{T_{sp}} + K_d \frac{de_{T_{sp}}}{dt} + K_i \int e_{T_{sp}} dt. \tag{27}$$

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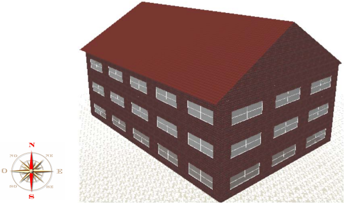
Examples

Case study

- A case study of a Milan's directional building (Northern Italy) on a typical cooling season ranging from April to September, typical day for month, was analysed.

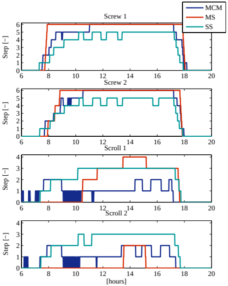
	Case 1	Case 2	Case 3
Chiller model	TCAE4320	TCAVBZ2600	TCAVBZ2600 + TCAE4320
Number of chillers	6	3	2 + 2
Nominal cooling capacity	1897.2 [kW]	1822.2 [kW]	1847.2 [kW]
Plant water content	2 [l/kW]	2 [l/kW]	2 [l/kW]
Temperature differential	1 [°C]	1 [°C]	1 [°C]
Supply water temperature	7 [°C]	7 [°C]	7 [°C]

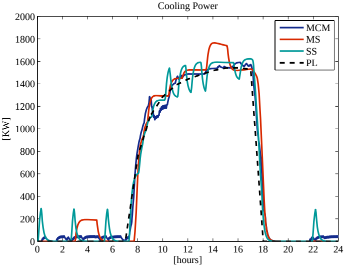


Example

Case 3: MPGA vs SS and MS strategies.

	Apr.	May	June	July	Aug.	Sept.	seasonal
Cooling energy MS [kWh]	4233	8612	11642	14315	12897	9973	61672
Cooling energy SS [kWh]	4242	8558	11620	14240	12545	9787	60992
Cooling energy MCM [kWh]	4123	8057	11535	14093	12548	9700	60057
EER MS	4.465	4.104	3.876	3.472	3.619	3.819	3.772
EER SS	4.451	4.341	3.871	3.560	3.626	4.008	3.853
EER MCM	4.611	4.395	4.036	3.611	3.700	4.044	3.931
ΔEER (MCM-MS) %	3.28	7.08	4.11	4.00	2.22	5.91	4.19
ΔEER (MCM-SS) %	3.61	1.24	4.25	1.42	2.04	0.91	2.01



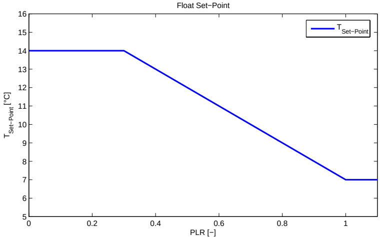


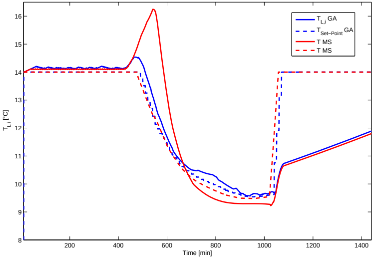
Floating Set-Point

The estimated cooling load of the building allows even to introduce, in the MCM algorithm, strategies for the adjustment of the building delivery systems water temperature, this to issue the real needs of ambients to be conditioned.

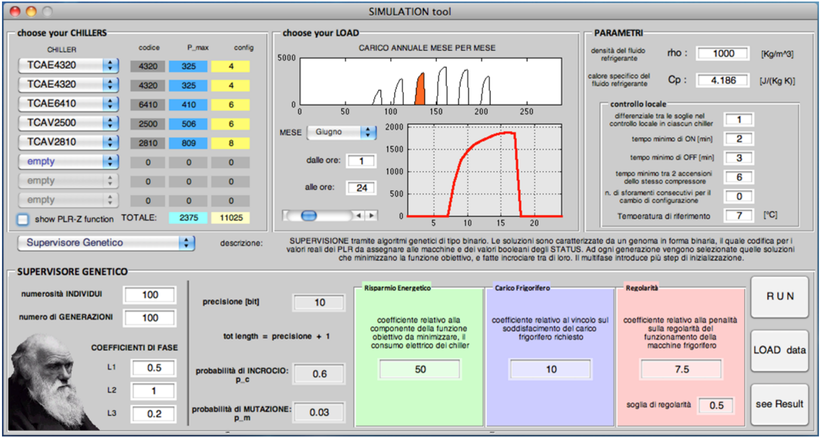
Case 3: MCM_{Flt} vs MCM, MS and SS strategies

	Apr.	May	June	July	Aug.	Sept.	seasonal
Cooling energy MCM_{Flt} [kWh]	4482	8928	1228	15093	13397	10233	64362
EER MCM_{Flt}	5.671	4.835	4.407	3.811	4.051	4.498	4.302
ΔEER $(MCM - MS)$ %	25.81	17.81	13.68	9.79	11.94	17.79	14.04
ΔEER $(MCM - SS)$ %	26.21	11.38	13.83	7.06	11.74	12.22	11.64
ΔEER $(MCM_{Flt} - MCM)$ %	21.81	10.02	9.19	5.56	9.50	11.22	9.37





Matlab/Simulink™ application



choose your CHILLERS

CHILLER	codice	P_max	config
TCAE4320	4320	325	4
TCAE4320	4320	325	4
TCAE6410	6410	410	6
TCAV2500	2500	506	6
TCAV2810	2810	809	8
empty	0	0	0
empty	0	0	0
empty	0	0	0
TOTALE:		2375	11025

☐ show PLR-Z function

choose your LOAD

MESE: Giugno
dalle ore: 1
alle ore: 24

PARAMETRI

densità del fluido refrigerante rho : 1000 [Kg/m^3]
calore specifico del fluido refrigerante Cp : 4.186 [J/(Kg K)]

controllo locale

differenziale tra le soglie nel controllo locale in ciascun chiller: 1
tempo minimo di ON [min]: 2
tempo minimo di OFF [min]: 3
tempo minimo tra 2 accensioni dello stesso compressore: 6
n. di sforamenti consecutivi per il cambio di configurazione: 0
Temoeratura di riferimento: 7 [°C]

Supervisore Genetico

descrizione: SUPERVISIONE tramite algoritmi genetici di tipo binario. Le soluzioni sono caratterizzate da un genoma in forma binaria, il quale codifica per i valori reali dei PLR da assegnare alle macchine e dei valori booleani degli STATUS. Ad ogni generazione vengono selezionate quelle soluzioni che minimizzano la funzione obiettivo, e fatte incrociare tra di loro. Il multifase introduce più step di inizializzazione.

SUPERVISORE GENETICO

numerosità INDIVIDUI: 100
numero di GENERAZIONI: 100

COEFFICIENTI DI FASE
L1: 0.5
L2: 1
L3: 0.2

precisione [bit]: 10
tot length = precisione + 1
probabilità di INCROCIO: p_c: 0.6
probabilità di MUTAZIONE: p_m: 0.03

Risparmio Energetico
coefficiente relativo alla componente della funzione obiettivo da minimizzare, il consumo elettrico dei chiller: 50

Carico Frigorifero
coefficiente relativo al vincolo sul soddisfacimento del carico frigorifero richiesto: 10

Regolarità
coefficiente relativo alla penalità sulla regolarità del funzionamento della macchine frigorifero: 7.5
soglia di regolarità: 0.5

Summary

- The problem of optimizing the operation of multi-chiller systems has been addressed.
- The OCL and OCS problems are solved making use of information on the actual thermal load applied to the plant.
- The performance of the algorithm has been evaluated by means of simulation performed with a dynamic model of the plant.
- The results show that it is possible to achieve substantial energy savings while granting good satisfaction of the cooling demand, if compared with standard MCM algorithms.

- Outlook
    - Optimal chiller operations by PSO algorithms.
    - Implementation of the algorithm on a commercial supervisory system is presently under development.
    - The approach can also be extended to include the management of more complex systems comprising air handling units and radiant and fan coil systems.
    - Furthermore, information from load forecasting models for the energy and economic management of thermal storages could be easily exploited by simple modifications of the load estimation scheme and performance index.
    - Optimal chiller selection in HVAC systems.

Publications

- A. Beghi, M. Bertinato, L. Cecchinato, and M. Rampazzo. *A multi-phase genetic algorithm for the efficient management of multi-chiller systems*. In Proceedings of the 7th Asian Control Conference, Hong Kong, China, August 27-29, 2009.
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- A. Beghi, L. Cecchinato and M. Rampazzo. *On-line, auto-tuning regulation of Electronic Expansion Valve for evaporator control.* In Proceedings of the 7th IEEE International Conference on Control & Automation (ICCA'09), December 9-11, 2009, Christchurch, New Zealand.
- A. Beghi, L. Cecchinato, and M. Rampazzo. *A multi-phase genetic algorithm for the efficient management of multi-chiller systems*. Submitted to Energy Conversion and Management, Feb. 2010.
- M. Albieri, A. Beghi, M. Bertinato, L. Cecchinato, M. Rampazzo and A. Zen. *Metodo e sistema per controllare una pluralità di macchine frigorifere di un impianto di climatizzazione*. Submitted patent, Rhoss S.p.A. (Codroipo-Italy), 2009.
- A. Beghi, L. Cecchinato and M. Rampazzo. *On-Line, Auto-Tuning Control of Electronic Expansion Valve.* Submitted to International Journal of Refrigeration, Feb. 2010.
- A. Beghi, L. Cecchinato, G. Cosi and M. Rampazzo.*Two-Layer Control of Multi-Chiller Systems.* Submitted to the 2010 IEEE Multi-Conference on Systems and Control (MSC), Yokohoma, Japan, September 8-10, 2010.
- S. Bolognani, F. Gambato, M. Rampazzo and A. Beghi. *Efficient Conditioning of Energy in AFE-Based Distributed Generation Units.* Submitted to the 2010 IEEE Multi-Conference on Systems and Control (MSC), Yokohoma, Japan, September 8-10, 2010.

Thank you for your attention

- Discussion and questions !?
- email: mirco.rampazzo@dei.unipd.it