On the (intelligent) control of solar thermal plants.

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OUTLINE

- Solar energy
- Thermal Solar plants control issues
- Parabolic trough plants
- Control experiences on commercial plants
- ERC Advanced Grant OCONTSOLAR
- Conclusions
Woody Allen:

“I took a speed reading course and read 'War and Peace' in twenty minutes. ... 

..... It involves Russia.”
The cosine factor
Extraterrestrial daily solar radiation and latitude

Diagram showing daily extraterrestrial irradiation—horizontal surface (MJ/m²) versus month for different latitudes (0°, 40°, 80°).
Average daily solar energy in Spain

Zona I: H < 3.8
Zona II: 3.8 ≤ H < 4.2
Zona III: 4.2 ≤ H < 4.6
Zona IV: 4.6 ≤ H < 5.0
Zona V: H ≥ 5.0
H se mide en kWh/m²

Source INM
Solar power systems covering the dark disks could provide more than the world's total primary energy demand (assuming a conversion efficiency of 8%).
Use of solar energy

Solar Thermal Collectors → Storage → Power Cycle (powerplant or engine) → Electricity Load (grid-connected or stand-alone)

Solar Thermal Collectors → Storage → AUX.

Photovoltaic Collectors → AUX. → Storage → AUX.
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Photovoltaic units

Fixed

Solar tracking: 1 axis

Solar tracking: 2 axis (and concentration)

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Concentrating Solar Power

Power tower

Parabolic trough
Control problems in solar systems

- Collectors movement (sun tracking)
  - Slow
  - Open loop (most of the time)

- Control of thermodynamic variables
  - Rich dynamics (PDEs, deadtimes, nonlinear, ...)
  - High disturbances
  - Closed loop (most of the time)
Parabolic trough fine tracking
Solar field

Parabolic trough

Inlet oil Temp.

Air Temp.

Solar radiation

Oil flow

Outlet temp.
Process model

Metal: \( \rho_m C_m A_m \frac{\partial T_m}{\partial t} = \eta_o I G - G H_l(T_m - T_a) - LH_t(T_m - T_f) \)

Fluid: \( \rho_f C_f A_f \frac{\partial T_f}{\partial t} + \rho_f C_f q \frac{\partial T_m}{\partial x} = LH_t(T_m - T_f) \)

Simulink model can be downloaded from:


http://www.esi2.us.es/~eduardo/libro-s/libro.html
Why controlling the solar plants is a challenge?

- The energy source is not a manipulated variable but a perturbation!

- Complex dynamics: Non linear, PDE, dead time, never at a steady state

- Constraints (operating closed to constraints)

- Deciding the operating mode is part of the control strategy (when to store energy).
Many contributors and many control techniques!

- R. Carmona (1985)
- F.R. Rubio (1985)
- J.A. Gutierrez (1987)
- M. Hughes (1992)
- M. Berenguel (1995)
- J. Normey (1997)
- M. R. Arahal (1997)
- L. Valenzuela (2005)
- C. M. Cirre (2006)
- M.P. Parte (2005)
- I. Alvarado (2008)
- A. Gallego (2012-)
- L. Yebra (2017)
- J.R.D Frejo (2020)
- E. Masero (2021)
- S. R. Moreno (2021)
- A.S. del Pozo (2017- ..)
- J. M. Escaño (2019- ..)
- .....
- J. M. Lemos (1997)
- E. Mosca (1998)
- R.N. Silva (1997)
- L.M. Rato (1997)
- M. Brao (2000)
- E. Juuso (2000)
- I. Farkas (2002)
- I. Vajk (2002)
- .....

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On the Control of Solar thermal Plants
MPC successful in industry.

Many and very diverse and successful applications:

- Petrochemical, polymers,
- Semiconductor production,
- Air traffic control,
- Clinical anesthesia,
- ...


Many MPC vendors
Members asked to assess impact of several advanced control technologies:

**Q1 Responses [23 responses]**
- PID control:  23 High-impact
- **Model-predictive control:**  18 High-impact; 2 No/Lo impact
- System identification: 14 High-impact; 2 No/Lo impact
- Process data analytics: 14 High-impact; 4 No/Lo impact
- Soft sensing: 12 High-impact; 5 No/Lo impact
- Fault detection and identification [22]: 11 High-impact; 4 No/Lo impact
- Decentralized and/or coordinated control: 11 High-impact; 7 No/Lo impact
- Intelligent control: 8 High-impact; 7 No/Lo impact
- Discrete-event systems [22]: 5 High-impact; 7 No/Lo impact
- Nonlinear control: 5 High-impact; 8 No/Lo impact
- Adaptive control: 4 High-impact; 10 No/Lo impact
- Hybrid dynamical systems: 3 High-impact; 10 No/Lo impact
- Robust control: 3 High-impact; 10 No/Lo impact
Why is MPC so successful?

- MPC is Most general way of posing the control problem in the time domain:
  - Optimal control
  - Stochastic control
  - Known references
  - Measurable disturbances
  - Multivariable
  - Dead time
  - Constraints
  - Uncertainties
Real reason of success: Economics

MPC can be used to optimize operating points (economic objectives). Optimum usually at the intersection of a set of constraints.

Obtaining smaller variance and taking constraints into account allow to operate closer to constraints (and optimum).

Repsol reported 2-6 months payback periods for new MPC applications.
MPC strategy

At sampling time $t$, the future control sequence is computed so that the future sequence of predicted output $y(t+k/t)$ along a horizon $N$ follows the future references as best as possible.

The first control signal is used and the rest disregarded.

The process is repeated at the next sampling instant $t+1$. 

![Diagram showing control actions and setpoint](attachment:image.png)
Errors minimized over a finite horizon

Constraints taken into account

Only the first control move is applied

Model of process used for predicting

Constraints taken into account
Only the first control move is applied again
MPC strategy

1. Optimization problem $P_N(x,\Omega)$:

   $u^* = \arg\min_u \sum_{i=0,...,N-1} l(x(i),u(i)) + F(x(N))$

   Operating constraints:
   
   $x(i) \in X, u(i) \in U, \ i=0,...,N-1$

   Terminal constraint (stability): $x(N) \in \Omega$

2. Apply the receding horizon control law:

   $K_N(x) = u^*(0)$. 
Linear MPC

\[ f(x,u) \] is an affine function (model)

\[ X,U,\Omega \] are polytope (constraints)

\[ l \text{ and } F \] are quadratic functions (or 1-norm or \( \infty \)-norm functions)

\[ \downarrow \]

QP or LP
Otherwise

If \( f(x,u) \) is not an affine function
Or any of \( X,U,\Omega \) are not polyhedra
Or any of \( l \) and \( F \) are not quadratic functions (or \( 1\text{-norm} \) or \( \infty\text{-norm} \) functions)

\[ \downarrow \]

Non linear MPC (NMPC)
Non linear (non necessarily convex) optimization problem much more difficult to solve.
(c) Día claro con nubosidad al final del día

(d) Día con perturbaciones en la radiación
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Spain (650 MWe)
• Solucar (3x50MWe)
• Helioenergy (2x50MWe)
• Solacor (2x50MWe)
• Helios (2x50MWe)
• Solaben (4x50MWe)

USA (560 MWe)
• Mojave (2x140 MWe)
• Solana (280 MWe)

South Africa
• Kaxu (100 MWe)
Solucar (3x50MWe)
Solucar (3x50MWe)
MPC application to real plants

- Solar field cannot be operated independently of steam generation system and turbines. It is necessary to take into account:
  - Steam pressure
  - HP valve aperture
  - Steam over-heating limitations
  - Power production limitations
  - Temperature gradients limitations
  - …
- Heuristic needed
MPC application to real plants (Intelligence)

- We took some time in the control center of two 50 MW plants learning from experienced operators.
- We analized operator responses and searched for patterns.
- We translated patterns into a program
Level 3. Real plant results
Level 3. Real plant results
Level 2: Simulation vs a day operation. A gain of 4.8 MWh (net) for a 50MW plant
Optimal Control of Thermal Solar Energy Systems
Advanced Research Grant
European Research Council
Solar trough energy plants will be taken as case studies
Objectives

1. Methods to control mobile sensor fleets and integrate them as an essential part of the overall control systems.

2. Spatially distributed solar irradiance estimation methods using a variable fleet of sensors mounted on drones and UGVs.

3. New model predictive control (MPC) algorithms that use mobile solar sensor estimations and predictions to yield safer and more efficient operation.
Conclusions

**MPC controllers:**
1. Always better than the best operator. Production increase between 0.5% and 2.5% depending on operator and day.
2. No constraint violations.
3. Production not relying on operator skills.
4. Short pay-back periods

**OCONT SOLAR:**
1. Better control and supervision with better information.
2. Initial studies have shown gains of around 4%.
Thanks

Some references


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