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Event-based MPC for defocusing and power production of a parabolic trough plant under power limitation

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ABSTRACT

Optimal operation of a solar plant is generally understood as a tracking of the optimal working temperatures which maximize the net electric power. However, a commercial solar plant may receive a limitation from the Transmission System Operator due to saturation of the electrical grid. In these situations the plant moves to an operation mode in which the objective is not maximum production but compliance with the orders of the Transmission System Operator.

The paper proposes an Event-Based Gain Scheduling Generalized Predictive Control strategy for electric power production reference tracking when power limitations are imposed by the Transmission System Operator. Gain Scheduling Generalized Predictive Controllers are proposed to control fourth and third collector defocus in order to prevent heating fluid temperature from exceeding the limits of the manufacturer and therefore, avoid oil degradation. A 50 MW parabolic solar trough plant model has been used to design and validate the strategy. Simulation results are presented showing the advantages of using the proposed strategy.

1. Introduction

During the second half of the 70s interest in renewable energies experienced a boost. This happened after the first oil crisis driven by economical factors when oil prices soared. After oil prices decreased, interest in renewable energies also decreased. Due to global warming and with the objective of reducing harmful emissions from conventional fossil power plants, interest in renewable energies has, once again, resurged (Goswami et al., 2000; Blanco and Santigosa, 2017). Currently, the renewable energies with the greatest impact on society are solar, wind and hydraulic, solar energy being the most abundant renewable energy by far.

This paper deals with the operation of parabolic solar plants. A parabolic solar plant consists of a field of parabolic-cylinder collectors arranged in loops with a cold oil inlet and hot oil outlet. The collectors focus direct solar radiation on a receiver tube through which oil circulates to heat it and send it to a heat exchanger. The next step is the steam cycle or power cycle where a steam turbine will produce electric energy.

Several Concentrating Solar Power (CSP) plants with Parabolic Trough Collectors (PTC) have been built around the world in the last decade. Examples of commercial CSPs currently producing are: 50 MW Andasol solar plants (Solar Millennium AG, 2018), Helios 1/2, 50 MW CSPs (220 hectares, 90 loops) (Helios 1, 2018), Khi Solar One in South Africa (operational since 2016) (Khi Solar One, 2018) and Solana CSP (Arizona, USA) with a gross turbine capacity of 280 MW (777 hectares, 808 loops) (Solana Generating Station, 2018). One of the advantages of CSP plants is the possibility of using thermal energy storage (Camacho et al., 2011; Alva et al., 2017; Sarbu and Sebarchievici, 2018). Generally, this is done by using molten salt tanks (hot and cold) (Solana Generating Station, 2018; Kaxu Solar One, 2018).

Generally, the main objective of the control systems in solar trough plants is to maintain the outlet temperature of the field around a desired set-point. Unlike conventional fossil fuel plants where the main source of energy (fuel) can be manipulated, in solar plants the main source of energy is considered a disturbance since the plant controller will have to deal with radiation transients due to clouds. In addition to clouds the daily beam radiation profile cycle is another source concern, as it affects the available solar energy. Research to improve performance in order to optimize solar power plants from the control point of view has been addressed in many ways. In most of the research works, the design of controllers is based on the ACUREX model, a parabolic trough field plant for research and experimental purposes, located in Almería, Spain (Camacho et al., 2012; Beschi et al., 2014; Lemos et al., 2014; Khoukhi et al., 2015; Alsharkawi and Rossiter, 2017).

As stated above, most of the works focus on new optimized control

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Nomenclature

A	cross-sectional area of the pipe (m^2)
C	specific heat capacity J/(kg° K)
D	hydraulic diameter of the pipe (m)
G	collector aperture (m)
H_l	global coefficient of thermal loss (W/(m^{2}° K))
H_t	coefficient of heat transmission metal-fluid (W/(m^{2}° K))
I	solar radiation (W/m^2)
k	thermal conductivity (W/(m·K))
K_{opt}	optical efficiency
L	length of pipeline (m)
n_o	geometric efficiency
Nu	Nusselt number
P	power (MW)
P_{cp}	fixed factor (loop geometrical and thermal properties)
phi	fixed factor
Pr	Prandtl number
PW_{ref}	reference to the Power GS-GPC
$PW_{set-point}$	power set-point by TSO
PW_{TSO}	boolean variable indicating the plant is on limitation mode
Q	oil flow rate (m^3/s, m^3/h, kg/s)
q_{ff}	computed flow-rate for one loop
Q_{ff}	computed flow-rate for the complete field
Q_{high}	flow limit to consider the plant is saturated
Q_{low}	flow limit to consider the plant is not saturated
Q_{PW}	flow-rate computed by the Power GS-GPC
Re	Reynolds number
S	total reflective surface (m^2)
t	time (s)
T	temperature (°C,K)
T_a	ambient temperature
T_{C3}^i	third collector temperature, loop i
T_{in}	inlet temperature
T_{out}	outlet temperature
T_{mean}	mean temperature between inlet and outlet temperature
T_{low}	field outlet temperature to consider the plant is not saturated
T_{high}	field outlet temperature to consider the plant is saturated
T_{ref}	temperature reference provided by the GS-GPC controller to the FeedForward
T_{ref-C3}	temperature set-point applied to the 3rd collector
T_{ref-C4}	temperature set-point applied to the 4th collector
$T_{ref-sat}$	temperature set-point for the 4th collector in saturation
$T_{ref-nosat}$	temperature set-point for the 4th collector not in saturation
TSO_L	boolean variable indicating a power limitation arrived
x	space (m)
ΔT	the thermal difference (°C)
β_k^i	defocus angle, 4th collector, loop i, instant k (deg)
β_{k-1}^i	defocus angle, 4th collector, loop i, instant $k-1$
γ_k^i	defocus angle, 3th collector, loop i, instant k
γ_{k-1}^i	defocus angle, 3th collector, loop i, instant $k-1$
μ	dynamic viscosity of the fluid (Pa· s= N·s/m2 = kg/(m·s))
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
$\mu_{rankine}$	Rankine cycle efficiency
$\mu_{exchanger}$	heat exchanger efficiency
$\mu_{parasitics}$	Parasitic effects efficiency

methods for temperature set-point tracking, constraint compliance, state estimation, just to name out a few. One of the most widespread applied techniques is Model Predictive Control (MPC). MPC techniques applied to solar plants have shown to be effective, as in Limón et al. (2008) where a Robust control of ACUREX is proposed using MPC for tracking. A Neural Network based MPC is presented in Gil et al. (2014). In Alsharkawi and Rossiter (2016), authors developed a linear time-variant state space estimation to design a Dual mode MPC. A different MPC approach is developed in Lima et al. (2016) in which the authors designed a Filtered Dynamic Matrix Control (FDMC). Authors used a filter for the prediction error so that the robustness of the control strategy is ensured. However, these works are focused on the tracking of a temperature set-point, rejection of disturbances, robustness, estimation and stability, just to name out a few.

Some of the most important topics in solar plants are costs reduction and the optimization of the plant operation (N.A Engineering, 2008; Blanco and Miller, 2017). Some examples can be found in Montes et al. (2009) where a standard methodology for the economic optimization of the solar multiple in parabolic trough plants is presented. Wittmann et al. (2011) presented a methodology on how to set up an economically optimized bidding strategy at the energy exchange. The objective was to achieve maximum benefit from the production and selling price point of view. In Camacho and Gallego (2013) an optimization of the temperature operating point for solar plants is presented. The optimal temperature set-point is obtained throughout the day depending on the environmental conditions. An optimal turbine inlet pressure of a CSP plant is calculated in Desai and Bandyopadhyay (2015). This works states that the optimal turbine inlet pressure is a weak function of design radiation. However, the optimum value increases with plant size and various modifications of Rankine cycle. In Sánchez et al. (2018), the authors proposed an online non-linear model based optimization to control the inlet valves. The objective is to homogenize the solar field to avoid the loss of electric production due to dirt (different loop efficiencies).

However, there are situations in which the plant has to move into an operation mode in which the optimization of the produced power does not make sense. A commercial solar plant may receive commands of power limitation from the Transmission System Operator (TSO). Typically, when the electrical grid is saturated. In these cases, the plant is forced to decrease its electric production and maintain the power set-point determined by the TSO. Therefore, maximum power production no longer makes sense. In this situations the objective is double: fulfilling the TSO power set-point and temperature tracking. The nominal operating point of a commercial plant is generally around the 393 °C field outlet temperature (Ibersol 1, 2018; Solaben 2, 2018). The plant will have a time period to reduce its generated electric power to the set-point determined by the TSO. If the plant does not comply with the determined set-point it would face economic sanctions. To decrease power it is necessary to decrease the oil flow-rate that reaches the heat exchanger where the steam phase begins. Plants with Thermal Energy Storage (TES) are able to deal with this situation, at least for a while, by diverting part of the flow-rate to the TES until these are saturated. Plants that do not have TES cannot cope with this so easily. This work focuses on plants that do not have TES such as Ibersol 1 (2018), Solaben 2 (2018), Guzmán (2018), Helios 1 (2018). Decreasing the flow-rate increases the outlet temperature. However, if the flow-rate is used to control the power, a new mechanism is necessary to control the field outlet temperature at the nominal operating point. This mechanism is the defocusing of collectors. This is done by augmenting the incidence angle between the solar beam and the normal to the mirror plane and thus the efficiency decreases. Typically, this control is only used in commercial plants to prevent the oil temperature from exceeding a maximum from which the oil begins to degrade. The main motivation of this paper is dealing with the operation of a parabolic trough plant under power limitation.

In this work, a novel Event based Gain Scheduling Generalized