UNIVERSIDAD DE SEVILLA
ESCUELA TECNICA SUPERIOR DE INGENIERIA

PhD THESIS

MODEL PREDICTIVE CONTROL AND OPTIMIZATION OF SOLAR THERMAL ENERGY PLANTS

Adolfo Juan Sánchez del Pozo Fernández

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A thesis submitted to the Departamento de Ingeniería de Sistemas y Automática, Escuela Técnica Superior de Ingeniería, in fulfilment of the requirements for the degree of Doctor of Philosophy, Universidad de Sevilla, España

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A mi familia

To my family

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Try not to become a man of success, but rather try to become a man of value.

Albert Einstein

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Intenta no convertirte en un hombre de éxito, sino más bien intenta convertirte en un hombre de valor.

Albert Einstein

Abstract

Model Predictive Control and Optimization of Solar Thermal Energy Plants

Adolfo Juan Sánchez del Pozo Fernández

The goals of the thesis are the development of new model predictive control strategies and optimization of large-scale parabolic solar plants. The thesis focuses on three aspects of the control of solar plants: (1) defocusing of the collectors, (2) control of solar plants in the presence of limitations of electric power and (3) optimization of the solar field. The design of the proposed controllers and the results obtained in the thesis are based on two solar field simulation models, the ACUREX field and a 50 MW commercial solar plant.

It is important to keep the oil temperature within the safe temperature limits provided by the manufacturer and to avoid its degradation. To prevent the temperature from exceeding the degradation limit commercial plants have a safety collector defocus strategy. This is applied in a staggered manner as total or partial defocusing, which is done by modifying the angle of the collector. This mechanism of defocusing the collector is reactive and highly inefficient due to the thermal jumps caused by the application of full or partial defocusing. In this thesis new Model Predictive Control (MPC) algorithms for the defocusing of the solar field loops collectors are presented. Event-based Generalized Predictive Control and State Space Model Predictive Control strategies will be applied for the defocusing of the fourth and third collector of the solar field loops.

An Event-based Generalized Predictive Control strategy for the generated electrical power tracking is presented. This controller is designed for cases in which the plant has to move to a special operation mode, ”power limitation”. This situation arises when the plant receives an order from the Transmission System Operator (TSO) indicating that the power generation must be reduced. In these cases, the plant is forced to decrease its electric production and maintain the power set-point determined by the TSO. In these situations the objective is double: fulfilling the TSO power set-point and temperature tracking. In these situations it will be very important to take into account the defocus strategy to avoid overheating the Heat Transfer Fluid (HTF) (usually oil).

In addition to the proposed algorithms for defocus and power limitation, a part of the thesis will focus on the optimization of the solar field. It will focus on obtaining a homogenization of the solar field (thermal balance). It will take into account factors such as the difference of the reflectivity in each of the loops, causing big differences in the temperatures of the loops. This may result in power losses, high temperature gradients between the loops and unnecessary defocusing actions with the corresponding deterioration of the actuators, flexible hoses and structures.

Nonlinear model based optimization algorithms are proposed for the control of the inlet valves of each of the loops in order to homogenize the solar field outlet temperature, or what is the same, a dynamic thermal balance of the solar field. This balance will decrease the high temperature differences between the different loops as well as the possible loss of energy due to unnecessary defocusing of part of the solar field with higher optical efficiency or higher solar radiation. In a final part of the thesis, the optimization algorithm developed for the field thermal balance will be applied in cases of partial cloudiness over the solar field. Given that commercial plants occupy very large land extensions, it is possible that part of the field is covered by clouds while other parts are not. This will cause the loops with less solar radiation to be at lower temperatures than other parts of the solar field. The global solar field outlet temperature controller may be working correctly (solar field outlet temperature tracking), but in order to achieve its objective it will decrease the flow rate, making the loops with more radiation reach the point of defocusing, resulting in energy losses.

Resumen

Control Predictivo basado en Modelo y Optimización de Plantas de Energía Solar Térmica

Adolfo Juan Sánchez del Pozo Fernández

Los objetivos de la tesis son el desarrollo de nuevas estrategias de control predictivo basadas en modelo y optimización de plantas solares parabólicas a gran escala. La tesis se centra en tres aspectos del control de plantas solares: (1) Desenfoque de los colectores, (2) control de plantas solares en presencia de limitaciones de potencia eléctrica y (3) optimización del campo solar. El diseño de los controladores propuestos y los resultados obtenidos en la tesis se basan en dos modelos de simulación de campo solar, el campo ACUREX y una planta solar comercial de 50 MW.

Es importante mantener la temperatura del fluido térmico dentro de los límites de temperatura de seguridad proporcionados por el fabricante y evitar su degradación. Para evitar que la temperatura exceda el límite de degradación, las plantas comerciales disponen de una estrategia de seguridad de desenfoque de colector. Esto se aplica de forma escalonada mediante desenfoque total o parcial, que se realiza modificando el ángulo del colector. Este mecanismo de desenfoque de colector es reactivo y altamente ineficiente debido a los saltos térmicos causados por la aplicación del desenfoque total o parcial. En esta tesis se presentan nuevos algoritmos de Control Predictivo basado en Modelo para el desenfoque de los colectores de los lazos del campo solar. Se aplicarán Controladores Predictivos Generalizados basados en eventos y Controladores Predictivos basados en Modelos en el espacio de estados para el control del desenfoque del cuarto y tercer colector de los lazos del campo solar.

Se presenta un Controlador Predictivo Generalizado basado en eventos para el tracking de potencia eléctrica generada. Este controlador se diseña para los casos en los que la planta se tiene que mover a un modo de operación especial, ”limitación de potencia”. Esta situación se produce cuando la planta recibe una orden del Operador del Sistema de Transporte indicando que se debe disminuir la potencia eléctrica generada. En estos casos, la planta se ve obligada a disminuir su producción eléctrica y mantener la consigna de potencia determinada por el Operador del Sistema de

Transporte. En estas situaciones el objetivo es doble: cumplir con el set-point de potencia indicado por el Operador del Sistema de Transporte y el seguimiento de la temperatura de salida de campo solar. En estas situaciones será muy importante tener en cuenta la estrategia de desenfoque para evitar sobrecalentar el fluido térmico (HTF) (generalmente aceite).

Además de los controladores propuestos para el desenfoque y limitación de potencia, una parte de la tesis se centrará en la optimización del campo solar. Se centrará en obtener una homogeneización del campo solar (balance térmico). Se tendrán en cuenta que factores como la reflectividad pueden ser diferentes en cada uno de los lazos provocando grandes diferencias en las temperaturas de los lazos. Esto puede provocar pérdidas de potencia, diferencias elevadas de temperatura entre los lazos y acciones innecesarias de desenfoque con el correspondiente deterioro de los actuadores, mangueras flexibles y estructuras.

Se proponen algoritmos de optimización basados en modelos no lineales para el control de las válvulas de entrada de cada uno de los lazos del campo solar con el fin de homogeneizar la temperatura de salida del campo solar, o lo que es lo mismo, un balance térmico del campo solar. Este equilibrio térmico disminuirá las grandes diferencias de temperatura entre los diferentes lazos, así como la posible pérdida de energía debido al desenfoque innecesario de parte del campo solar con mayor eficiencia óptica o mayor radiación solar. En una última parte de la tesis, se aplicará el algoritmo de optimización desarrollado para el balance térmico del campo en casos de nubosidad parcial sobre el campo solar. Dado que las plantas comerciales ocupan extensiones de terreno muy grandes, es posible encontrar que partes del campo estén cubiertas por nubes mientras que otras partes no lo estarán. Ésto provocará que los lazos con menor radiación solar se encuentren a temperaturas muy inferiores a otras partes del campo solar. El controlador global de temperatura de salida de campo solar podrá estar funcionando correctamente (seguimiento de la temperatura de salida de campo solar), pero para poder cumplir con su objetivo disminuirá el caudal haciendo que los lazos con más radiación puedan alcanzar el punto de desenfoque, produciendose pérdidas de energía.

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Acronyms

BESS	Battery Energy Storage System
CARIMA	Controlled Auto Regressive Integrated Moving Average
CART	Classification and Regression Tree
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CPM	Concentrated (Lumped) Parameter Model
CSP	Concentrated Solar Plant
DNI	Direct Normal Irradiance
DPM	Distributed Parameter Model
EGS-GPC	Event Based Gain Scheduling Generalized Predictive Control
EKF	Extended Kalman Filter
FDMC	Filter Dynamic Matrix Control
FF	Feed Forward
GA	Genetic Algorithm
GPC	Generalized Predictive Control
GS	Gain Scheduling
GS-GPC	Gain Scheduling Generalized Predictive Control
HCE	Heat Collector Element
HTF	Heat Transfer Fluid
ISE	Integral Square Error
ITAE	Integral of Time Absolute Error
LFC	Linear Fresnel Collector
LFR	Linear Fresnel Reflector
MLD	Mixed Logical Dynamical (MLD) model
MPC	Model-based Predictive Control
NLVC	Nonlinear Valve Control
NMPC	Nonlinear Model Predictive Control

OCONTSOLAR	Optimal Control of Thermal Solar Energy Systems
PDE	Partial Differential Equation
PID	Proportional Integral Derivative
PNMPC	Practical Nonlinear Model Predictive Controller
PSA	Plataforma Solar de Almería
PTC	Parabolic Trough Collector
PTPP	Parabolic Trough Power Plant
QP	Quadratic Programming
RMSE	Root Mean Square Deviation
SCA	Solar Collector Assembly
SEGS	Solar Electric Generation Stations
SISO	Single Input Single Output
TES	Thermal Energy Storage
TP	Triangular Partition
TSO	Transmission System Operator
UAV	Unmanned Aerial Vehicle
UKF	Unscented Kalman Filter

Nomenclature

A	Cross-sectional area of the pipe (m^2)
$C(t,T)$	Specific heat capacity $(\mathrm{J}/(\mathrm{kg}^\circ\mathrm{C}))$
D	Hydraulic diameter of the pipe (m)
G	Collector aperture (m)
$H_l(t,T)$	Thermal loss global coefficient $(\mathrm{W}/(\mathrm{m}^{2o}\mathrm{C}))$
$H_t(t,T,q)$	Metal-fluid heat transmission coefficient $(\mathrm{W}/(\mathrm{m}^{2o}\mathrm{C}))$
$I(t)$	Direct solar radiation $(\mathrm{W}/\mathrm{m}^2)$
$k(t,T)$	Thermal conductivity $(\mathrm{W}/(\mathrm{m}^\circ\mathrm{C}))$
K_{opt}	Optical efficiency (Unitless)
L	Length of pipeline (m)
$n_o(t)$	Geometric efficiency (Unitless)
Nu	Nusselt number
P	Power (MW)
P_{ref}	Reference to the Power GS-GPC (MW)
$P_{set-point}$	Power set-point by TSO (MW)
P_{TSO}	Boolean variable indicating the plant is on limitation mode
TSO_L	Boolean variable indicating the plant received a power limitation
P_{cp}	Fixed factor (loop geometrical and thermal properties) $\mathrm{J}/(\mathrm{m}^{3o}\mathrm{C})$
phi	Fixed factor (Unitless)
$q(t)$	Loop oil flow rate $(\mathrm{m}^3/\mathrm{s})$
$Q(t)$	Solar field oil flow rate $(\mathrm{m}^3/\mathrm{h}, \mathrm{kg}/\mathrm{s})$
q_{ff}	Computed flow-rate by the Feed Forward (1 Loop) $(\mathrm{m}^3/\mathrm{s})$
Q_{ff}	Computed flow-rate by the Feed Forward (N Loops) $(\mathrm{m}^3/\mathrm{s})$
Q_{high}	Flow limit to consider the plant is saturated $(\mathrm{m}^3/\mathrm{h})$
Q_{low}	Flow limit to consider the plant is not $(\mathrm{m}^3/\mathrm{h})$
Q_{PW}	Power GS-GPC Flow-rate $(\mathrm{m}^3/\mathrm{s})$
Re	Reynolds number
S	Total reflective surface (m^2)
t	Time (s)

$T(x,t)$	Temperature (°C)
$T_a(t)$	Ambient temperature (°C)
T_{C3}^i	Third collector temperature (loop i) (°C)
T_{in}	Inlet temperature (°C)
T_{out}	Outlet temperature (°C)
T_{mean}	Mean temperature between inlet and outlet temperature (°C)
T_{ref}	Virtual temperature reference sent to the FF (°C)
$T_{set-point}$	Temperature reference for tracking (°C)
T_{high}	Field outlet temperature to consider the plant is saturated (°C)
T_{low}	Field outlet temperature to consider the plant is not saturated (°C)
T_{ref-C3}	Temperature set-point applied to the 3^{rd}collector (°C)
T_{ref-C4}	Temperature set-point applied to the 4^{th}collector (°C)
$T_{ref-sat}$	Temperature set-point for the 4^{th} collector in saturation (°C)
$T_{ref-nosat}$	Temperature set-point for the 4^{th} collector not in saturation (°C)
x	Space (m)
ΔT	Thermal difference (°C)
β_k^i	Defocus angle, 4^{th} collector, loop i, instant k (deg)
γ_k^i	Defocus angle, 3^{th} collector, loop i, instant k (deg)
$\mu(t,T)$	Dynamic viscosity of the fluid ($\mathrm{Pa\cdot s}$)
$\mu_{col}(t)$	Collector defocus efficiency (Unitless)
$\nu(t,T)$	Kinematic viscosity of the fluid ($\mathrm{m^2/s}$)
$\rho(t,T)$	Density ($\mathrm{kg/m^3}$)
η_{ext}	Efficiency considering other effects (Unitless)
η_{par}	Parasitics efficiency (Unitless)
η_{rank}	Rankine cycle efficiency (Unitless)

Chapter 1

Introduction

1.1 Solar Energy: History

Almost the vast majority of the energy used by animals, plants and other living beings, including the energy we use to generate electricity, comes directly or indirectly from the sun. Observing the natural cycle of life and the food chain on earth, plants absorb solar energy directly in order to perform the photosynthesis cycle. In a later step, the herbivores, eat these plants and therefore absorb a part of this solar energy. Similarly, carnivores, by eating other animals, including herbivores, indirectly absorb a smaller amount of this energy. Thus, most renewable energy sources, such as wind or hydraulics used by man, derive indirectly from the Sun [1].

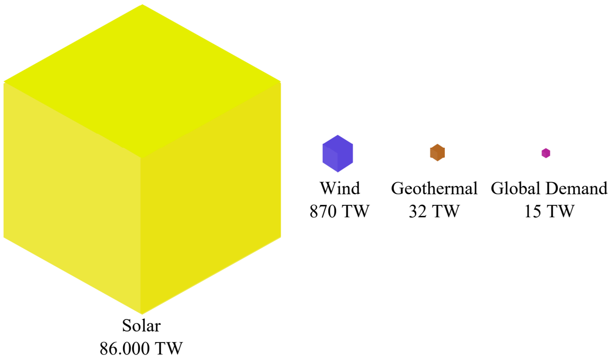

Figure 1.1: Solar energy power comparative

It is even present in the generation of electrical energy at present in the fossil fuels fuel generation plants. The solar energy generated millions of years ago was captured through photosynthesis and preserved in this way until today. Hydropower uses the potential energy of water that, through the hydrological cycle (evaporation of ocean water, condensation and precipitation), can be used as a source of energy through dams and waterfalls. Wind energy is another form of use of solar radiation, since this, by heating with different intensity different areas of the earth's surface, gives rise to the winds, which can be used to generate electricity, move boats, pump groundwater and many other uses.

This document focuses exclusively on the direct use of radiation emitted by the sun and reaching the earth's surface.

The sun emits more than 160,000 TW of power towards the earth. This power does not completely reach the earth's surface. Around 86,000 TW of power reach the earth's surface while the rest are absorbed or reflected by the atmosphere, clouds and the earth's surface [2].

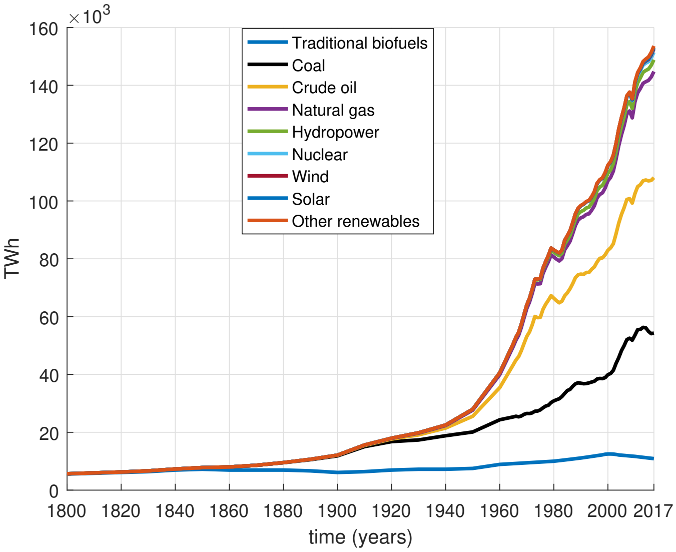

Figure 1.2: Global primary energy consumption. Source: Our World in Data [3]

A small fraction of the solar energy that reaches the surface would be enough to satisfy the global energy demand which continues to increase every year, see Fig. 1.2.

In a comparative way and as previously mentioned, the available wind energy is estimated at around 870 TW, which means 0.01% of the solar energy that reaches the earth's surface. Most of this wind energy is available over open ocean. The ocean covers 71% of the planet.

It is interesting to look back and examine how the sun's energy has been used in the past. From its first uses to the current solar thermal and photovoltaic plants, the way in which solar energy has been collected, the technology that has been used and the use that has been given to that energy has gone through many phases. In all these phases, the objective has always been the same: the maximum possible use of the immense amount of energy that the sun brings each day to planet earth.

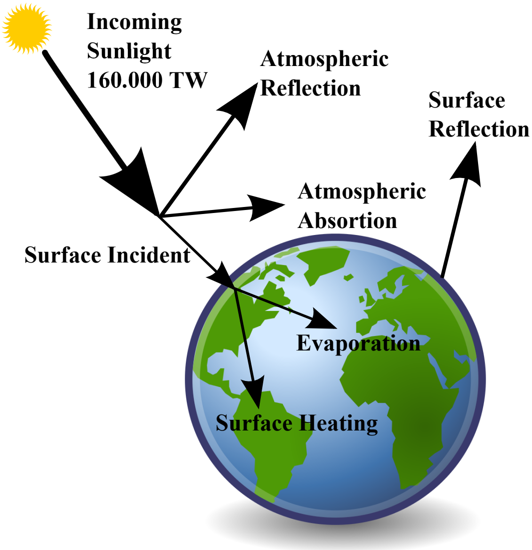

Figure 1.3: Solar energy reaching earth

It is quite difficult to specify a specific date on which contacts between human beings and solar energy began.

One of the first historical references of the use of concentrated solar energy that can be found is in ancient Greece, at the time of Archimedes. Archimedes, physicist, engineer, inventor, astronomer and Greek mathematician, invented for the Greek army a system to set on fire the enemy ships, by concentrating the solar energy at a point using mirrors. There are writings in which the use of mirrors made of bronze is reported to concentrate and reflect the solar light on the Roman fleet to burn it during the battle of

Syracuse (III century B.C.). Fig. 1.4 shows an illustration of Archimedes mirrors. However, this is part of a legend and it is not known how much of this is true in the writings. Centuries later, mirrors were used for metal smelting and burning of trees, among others [4].

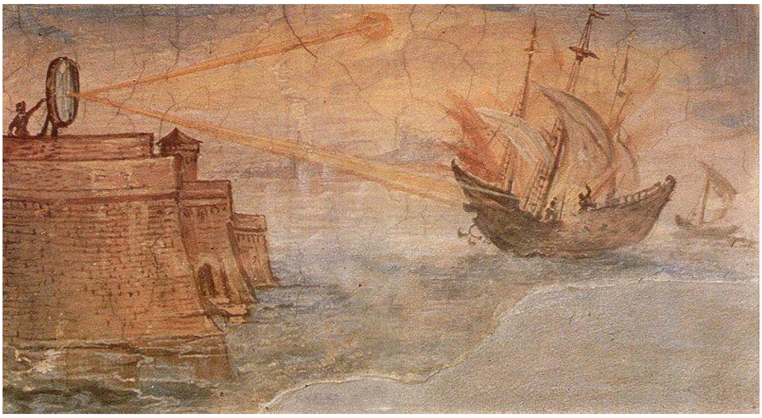

Figure 1.4: A wall painting from the Uffizi Gallery, Stanzino delle Matematiche, in Florence, Italy, shows the Greek mathematician Archimedes' mirror burning Roman military ships. Painted in 1600 by Gieulio Parigi

In 1515, Leonardo started one of his many projects, although it would never be finished. His project was to build a concave mirrors based solar concentrator for industrial steam and heat production.

In 1615, the French engineer Salomon de Caux engineered an engine, whose source was solar energy through glass lenses, which through the expansion of air could pump water [5]. It was the first recorded mechanical application of the Sun's energy.

It must be highlighted the work of Horace-Bénédict de Saussure in 1767. He wanted to see what temperature could be reached in a glass box thanks to the greenhouse effect. He managed to reach 109 C and without knowing it, he created the so-called solar collector. Antoine-Laurent de Lavoisier, French chemist, built in 1792 a solar oven consisting of two powerful lenses that concentrated the solar radiation in a focus point allowing him to reach high temperatures to melt metals.

The second half of the 19th century was especially interesting in the development of new techniques for capturing solar energy. Several were the pioneers during this stage who developed systems to heat domestic water, motors powered by the use of solar energy, as well as the first thermosolar plants.

Augustin Mouchot's conviction was that coal, which fueled the Industrial Revolution, was not going to last forever and led him to notice the energy that came from the Sun. In 1860 he built a solar kitchen and later he designed a water-filled boiler enclosed in glass, which would be exposed to the heat of the sun until the water boiled. A small steam engine motor would use the steam produced by the sun boiler. By August 1866, Mouchot had developed the first parabolic trough solar collector [6].

John Ericsson, Swedish engineer and inventor, designed in 1870 a solar collector attached to a 373 W hot air motor [7].

Charles Wilson, Swedish engineer, designed and built a desalination plant using solar energy in the desert of Atacama (Chile). This plant produced around 20,000 litres per day of fresh water [8].

In 1891, Clarence Kemp designed and patented the first water heater with solar energy thanks to the use of a collector. Registered the patent as 'Climax', promoting the commercial development of this type of energy [4].

Figure 1.5: Solar powered motor at the Cawston's Ostrich Farm. Source: DeGolyer Library [9]

In 1901, Aubrey Eneas built the first successful experiment of a solar powered motor for commercial used. He installed it at the Cawston's Ostrich Farm in South Pasadena, Fig. 1.5. The parabolic dish mirrors concentrated solar energy on a boiler to produce steam to power an engine to pump underground water to the ostrich farm and founded the first solar company, The Solar Motor Co. [10].

In 1909 William Bailey introduced a substantial improvement in the development of solar water heater. Bailey proposed and patented a solar water heater by dividing it into two stages. These stages would separate the water storage system from the solar system that would heat it by using a circulation and heat conservation system. Its design was the basis of solar heaters that are currently used [4].

One of the most ambitious was the American Frank Shuman. Shuman founded his company Sun Power Co. in 1911. In 1912-1913, he built the first parabolic trough solar plant in Maadi, Egypt. The plant, called "Solar Engine One", was composed of five 60 m length parabolic reflectors, north-south oriented, with a mechanical tracker mechanism to track the sun along the day to concentrate the sun rays in order to generate steam to pump 22,700 l/m approximately, to irrigate the desert near the Nile River. But his ambition had no limits, so he struggled to get a solar plant capable of generating all the energy consumed by the whole world. Shuman calculated that a 52,600 square kilometers parabolic trough plant, built in the Sahara, could produce the equivalent energy to all the fuel burnt in the world in 1909 [11]. Before the beginning of the war, Shuman reached agreements with the British and German governments for his proposal of solar energy in the tropics. The German Reichstag agreed to give an advance of 200.000 marks to start the project [12], but the start of World War I changed everything. Shuman's project was automatically paralyzed and all workers at the Maadi solar plant returned to Germany to fight on the German side. The installations at Maadi were destroyed. Schuman died during the course of the war in 1918. At the end of the war, with the defeat of Germany, the loss of all African colonies and the discovery of oil and gas reserves, which were sold at very low prices, the interest in solar energy was lost and Shuman's project fell into oblivion [13].

The oil crisis during the second half of the 70s caused an interest in renewable energy unprecedented, although this interest was not due to the renewable nature but to economic factors because oil prices soared. However, when oil prices decreased again, interest in renewables was lost. However, this interest has resurged, although not due to economic factors caused by the price of oil, but due to environmental awareness. Due to global warming and with the objective of reducing harmful pollutant gases emissions from conventional fossil power plants such as SO_2, CO, NOx, HC and CO_2, the interest in renewable energies has, once again, resurged [14–16]. Currently renewable energies with the greatest impact on society are solar, wind and hydraulic. Solar energy being, by far, the most abundant.

1.2 State of the Art

The first thermosolar plants for experimentation purposes were plants of reduced size, e.g., the old solar trough plant ACUREX and the new TCP-100 field in the Plataforma Solar de Almería (PSA) [17] or the Juelich solar tower research facility [18]. However, nowadays, commercial solar thermal power plants cover vast areas of land.

There are several current technologies to produce electricity from the direct solar radiation. Among them, the following stand out:

1. Solar Tower Power Plants
2. Linear Fresnel Reflector Power Plants
3. Solar Parabolic Trough Power Plants

1.2.1 Tower and Fresnel Power Plants

The solar thermal tower power plants are point-focus systems that concentrate the solar energy in a central receiver located at the top of a tower. A field of mirrors or ”heliostats” are in charge of reflecting the direct solar radiation in said receiver. This receiver will convert the concentrated heat into steam which will then be converted into electrical energy by means of a turbine. In general, a solar tower power plant is composed of the aforementioned tower and the field of heliostats that may surround it partially or completely depending on the number of receivers of the tower. For example, the PS10

(10 MW) and PS20 (20MW) towers, owned by Atlantica Yield [19], are made up of partial fields of heliostats as can be seen in Fig. 1.6, while in Fig. 1.7 shows the image of the Crescend solar plant in which it can be seen how the heliostat field completely surrounds the central tower. The heliostats have a solar tracking system for concentrating the sun's rays throughout the day [20]. This type of plants can also include thermal storage systems through the use of molten salts, generally nitrates, for power generation in periods without solar radiation.

Figure 1.6: PS20 PS10 solar tower plants in Sanlucar la Mayor, Seville, Spain. Source: Koza1983, Wikimedia [21]

Figure 1.7: Crescent Dunes Solar Energy Facility. Source: Amble, Wikimedia [22]

Solar tower plants are one of the most promising technologies for the production of electrical energy from solar energy. One of the aspects that continue to be part of the core of the research in this type of plants is the optimal design of the heliostat field. Its complexity is due to the annual performance of the field since it depends strongly on the location, the annual radiation periods and the positions between the heliostats that will cause shadows on other neighboring heliostats thus decreasing the solar energy collection [23].

The solar tower plants have maintained a constant development and have gone from experimental plants to plants of few MW and in the last years to hundreds of MW of production [24]. Among the tower plants that are currently in production, it can be found the already mentioned PS10 (10 MW) and PS20 (20 MW) in Seville (Spain) [25, 26], the Supcon Solar Project (50MW) in Delingha (China) [27], Crescent Dunes Solar Energy Facility in Nevada (United States) with a power production of 100 MW and an heliostat field covering 6,474,970 m^2 approximately [28], and the Ivanpah Solar Electric Generating System which is a set of three plants with a total gross production of 392 MW (126 MW, 133 MW and 133 MW) over 2,600,000 m2 [29], see Fig. 1.8.

Figure 1.8: Ivanpah Solar Power Facility (all towers online). Source: Sbharris, Wikimedia [30]

On the other hand, the Fresnel linear collectors or reflectors (LFC, LFR) differs both in the arrangement of the field and in the point and form of solar energy collection. The mirrors are arranged horizontally and linearly. A linear receiver located over the mirrors is responsible for receiving the energy and transferring it to the internal fluid. Unlike the tower and parabolic plants, the horizontal arrangement implies a lower relation between the aperture and optical efficiency. Although it is important that these plants occupy relatively little space, there must be a compensation for the loss of optical efficiency with a decrease in the cost per m^2 of aperture compared to parabolic solar plants. One of the advantages of LFC or LFR technology is the reduced cost due to the use of simple structures and flat mirrors whose manufacture is cheaper than the curved mirrors of the PTC. The use of flat mirrors makes the design of these plants differ, in general, in size, arrangement and dimensions of the mirrors [31, 32]. Companies such as SUNCINM or SOLTIGUA [33, 34], among others, compete in the development and installation of LFC plants.

Typically, the tower and parabolic trough plants have been the technologies used for the generation of electric power from solar energy in large scale. Fresnel plants began their development as solar thermal plants for low and medium scale such as Puerto Errado 1 Thermosolar Power Plant [35] in Murcia (Spain) with a power production of 1.4 MW. Given the small size of these plants it is interesting to use them on the roofs of the buildings for various services. As an example it can be highlighted the experimental Linear Fresnel Collector solar cooling plant located at the Engineering School (ESI) of Seville [36], see Fig. 1.9.

Figure 1.9: Linear Fresnel Collector solar cooling plant located at the Engineering School (ESI) of Seville

However, they are also beginning their large-scale development. Proof of these are the 30 MW Puerto Errado 2 Thermosolar Power Plant [37], covering 302,000 m^2 of land, sited in Murcia (Spain), see Fig. 1.10, and Dhursar Fresnel plant in Rajasthan (India) with a production of 125 MW and 3,000,000 m^2 of land area [38].

Figure 1.10: Novatec Fresnel Power Station Puerto Errado 2. Source: Novatec Solar, Wikimedia [39]

As an additional comment, it can be found another type of plants that is quickly spreading, photovoltaic plants (PV). Although these types of plants also use direct solar radiation (not exclusively), they are not considered solar concentration systems since the solar cells convert sunlight directly into electricity, therefore, they are outside the scope of this document. However, it should be noted that these types of plants can be used at any scale, being possible to find them both for large-scale use for the generation of large quantities of electrical energy as well as domestic and are becoming in a strong commitment to the integration of renewable sources in power distribution networks [40].

This thesis is mainly focused on cylinder-parabolic technology, although some of the concepts that are exposed are valid also for other of the described technologies.

1.2.2 Solar Parabolic Trough Power Plants

Parabolic Trough Power Plants (PTPP) also named as Parabolic Trough Collector (PTC) Concentrated Solar Plant (CSP) are formed by parallel rows of parabolic mirrors whose focal line is used to set a special receiving pipe through which a synthetic fluid circulates. Each of these rows are commonly called solar field loops and current commercial plants contain from several tens to several hundred loops.

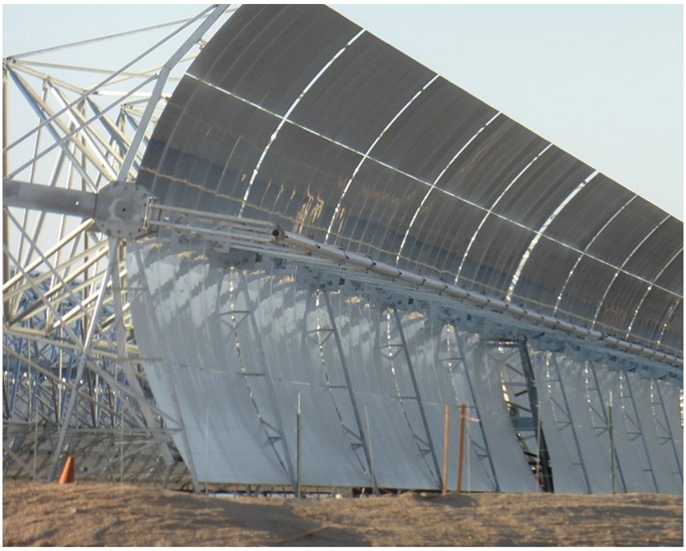

Figure 1.11: Parabolic Solar Collector at Mojave Desert, Mojave Solar Project. Source: Z22, Wikimedia [41]

Each of the loops that make up the solar field is composed of independent modules called Solar Collector Assemblies (SCA). In general, each of these SCAs are made up of the following elements:

1. Metal structure.
2. Parabolic reflectors (mirrors).
3. Absorber pipe (receiver tube).
4. Flexible hoses.
5. Tracking system, sensors and control.

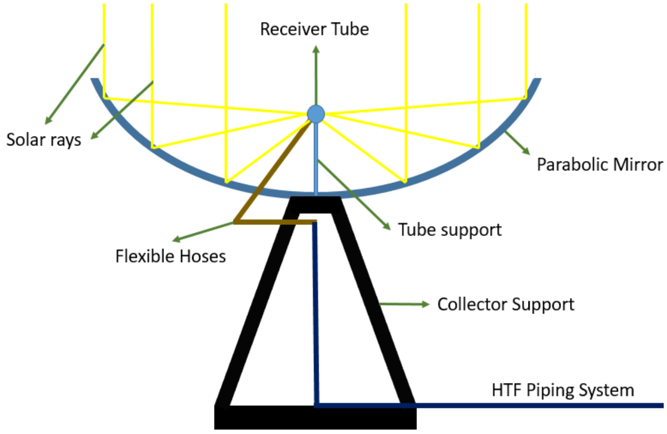

Figure 1.12: Parabolic collector schematic

The mirrors concentrate the direct solar energy in the focus line, where the receiver tube is, and the heat is transferred to the fluid that circulates through the pipe. The heated fluid is transported to the electric generation phase. By means of a heat exchanger the heat of the fluid is used to obtain steam and by means of a turbine electrical energy is generated. Although most generation systems in parabolic trough plants use heat exchangers for steam generation, there are other systems in which the steam is produced directly in the solar field [42].

The receiver tube or heat collection element (HCE), installed along the focal line of the loops, is composed of a thin metal pipe surrounded by a glass cover. In the space left between the metal pipe, where the HTF will flow, and the glass envelope, a vacuum is created to reduce thermal losses to the environment due to convection losses.

The solar tracking system is a fundamental element in PTC solar plants. It is important to know the angle between the solar rays and the surface or aperture of the collector. If the collector is not directly pointing to the sun, some of the energy is lost since it is not reflected on the focal line, which is where the receiver pipe with the thermal fluid is located [43].

The thermal fluid or most commonly known as Heat Transfer Fluid (HTF) is, generally, a synthetic thermal oil that supports high temperatures before its degradation. The vast majority of commercial parabolic cylinder plants currently work in temperatures in the range of 300 to 400 °C and use this type of oil. The nominal operating point of the plants that use synthetic oils is usually 393 °C [44–47]. Other types of materials, such as molten salts, can also be used as a heat transfer fluid and can withstand higher temperatures. The advantage of using molten salts instead of synthetic oils is that by raising the working temperature at the outlet of the solar field higher generation performance can be achieved since the efficiency of the Rankine cycle is increased [48]. However, the use of salts also entails some inconveniences. The main one is the increase in the operation and maintenance requirements of the plant. This is due to the freezing point of the molten salts. While the synthetic oils do not freeze up to about 15 °C, the tertiary and binary molten salts do so between 120 and 220 °C [49]. This high freezing point is a challenge in the use of this type of materials as thermal fluid. Routine protection and safety operations are necessary in case of freezing, since serious structural and economic damage to the plant could be generated.

But although molten salts present this drawback at the freezing point, they are still a key factor in the designs of parabolic trough plants. It is important to emphasize that one of the most relevant characteristics of this type of solar plants is the capacity to store energy [50–53], to be used later, e.g., when the sun has set . The storage of thermal energy can be done, generally, using steam [54] or molten salt tanks [55, 56], being molten salts the best option when storage capacity is increased [57]. Currently, most of the commercial plants use synthetic oil, such as *Therminol Vp1* and *DOWTHERM*^{TM}, as fluid for the solar field, while the molten salts are used mainly for thermal storage tanks.

Generally, the objective to pursue in PTC CSPs is to keep temperature at the outlet of the solar field around a reference value or set-point by using the flow-rate of the fluid as a control signal. The Direct Normal Irradiance (DNI) collected by the field is focused onto a tube whereby the Heat Transfer Fluid (HTF), normally a synthetic oil, circulates.

Multiple research efforts have been made in the field of PTC CSP control. Most of the research related to this field has been carried out in the ACUREX solar field sited in Almería (Spain) (PSA-CIEMAT) [58–63]. Studies have been done both in simulation models and in real tests in the ACUREX facilities since its commissioning in the 80s. ACUREX solar field was one of the first operational PTC plants with a 0.5 MW Stal-Laval turbine. Currently, this field is out of service and has been replaced by a new experimental field, the TCP-100 of 2.3 MWth, see Fig. 1.13. This experimental field was implemented in 2014 but it is not yet full operational. It has a solar field formed by 3 loops in parallel. Each loop is composed of 2 collectors (model TERMOPOWER) in series with a length of 100 m, and an aperture width of 5.77 m. The fluid used in the solar field is Syltherm-800 and the facilities has a thermocline storage tank with 115 m^3 of Santotherm-55 oil with a maximum operating temperature of 300 °C [64].

Figure 1.13: Top view of the new TCP-100 parabolic trough facilities in Almería (PSA-CIEMAT) (Spain)

The use of automatic control strategies in solar plants can help to maximize their performance. It must be taken into account that these plants are faced with multiple environmental disturbances such as radiation, cloudiness or ambient temperature, as well as the forced disturbances produced by the different phases of the solar plant, among which disturbances at the inlet temperature of the solar field should be highlighted. While in conventional fossil fuel power generating processes the main source of energy (the fuel) can be manipulated as the main control variable. Furthermore, the main source of energy itself is considered as a disturbance since the plant controller will have to deal with radiation transients due to clouds. The control

One of the most important parts of a solar thermal plant is the control system. This is topically divided in different levels. Each level will be in charge of different systems such as the controlling, monitoring and supervision of the facility. Other levels will be controlling small portions of the solar field solar reflectors as well as local PLC controllers performing local control of each collector such as sun tracking and safety mechanism [65].

The research groups have devoted great efforts in the solar thermal field in different aspects such as modeling, identification, simulation and control. Among the controllers proposed in the literature it can be found classic controllers such as PIDs, adaptive control, control using feedforward compensators (in series and in parallel), controllers based on gain scheduling tables, robust control, fuzzy logic controllers and neural networks, predictive control based on model and non-linear controllers.

The objectives that have been pursued in research related to the control of solar plants focus on temperature tracking, robustness, estimation and plant optimization, to name just but a few.

For example, In [58] a self-tunning PID including a feedforward series compensator is proposed and real tests at the ACUREX facilities are shown. [66] proposed a fuzzy logic controller for the ACUREX solar field using a special subclass of fuzzy inference systems, the TP (triangular partition) and TPE (triangular partition with evenly spaced midpoints) systems. [67] presented a Genetic Algorithm (GA) based Fuzzy logic controller for a solar distributed field. In [68] a constrained nonlinear controller is proposed by using nonlinear state-space neural networks which are trained online using an Unscented Kalman Filter (UKF). In [69], adaptative control and nonlinear schemes are described for the ACUREX solar field.

Regarding Model Predictive Control (MPC) strategies, it can be found, inter alia, an adaptive MPC to control a parabolic solar trough plant in [70], a Gain-Scheduled Control of solar power plant is design in [71, 72], and in [73] an Observer-based Model Predictive Control is developed. [74] presents a filtered Dynamic Matrix Control (FDMC) where a filter is used for the prediction error so that the robustness of the control strategy is ensured applied to a solar collector field and [75] proposes a Dual mode MPC for a concentrated solar thermal power plant based on an estimated linear time-invariant state space model around a nominal operating point. In [76], a practical Nonlinear MPC is developed for outlet temperature reference tracking. Robustness and stability are included by adding, to the cost function and in the controller constraints, a Lyapunov function. In [77] a Neural Network based MPC and Kalman Filter weighting computation is proposed for a distributed collector field. In [78], a review of the application of linear and nonlinear model predictive control algorithms to the ACUREX plant is presented.

Although the new TCP-100 experimental parabolic trough field for research purposes sited at Plataforma Solar de Almería (PSA-CIEMAT) is not yet operational, analysis and simulation studies of controllers have already begun as in [17] where a mathematical modeling of the new TCP-100 is developed and in [79] where a Gain Scheduling Model Predictive Control (GS-GPC) is presented for field outlet temperature tracking of the new TCP-100 solar infrastructures.

Regarding optimal operation, research is generally focused in economical design aspects and production maximization. [80] is focused on selling price and maximum benefit of the produced energy by applying an economic optimization while in [81] presented a model to determine the optimal day ahead offering strategy for CSP plants with TES, by solving an optimization problem which maximizes the expected total profit, in power markets. A new term penalizing the generation variation (cycling) is presented in [82], which is used for a scheduling strategy for CSPs. Authors showed that a reduction in the generation cycling can extend the lifetime of the power block without reducing profits. However, there is a lack of experimental research applied to commercial solar trough plants. An optimal operation in solar plants study is presented in [1]. Authors proposed a three layer algorithm to increase the performance by calculating the optimal solar field outlet temperature.

In the mid-80s the company Luz International Limited began to build what are considered the first commercial PTC solar plants, the Solar Electric Generation Stations (SEGS). The construction between 1984 and 1991 of the 9 plants that make up the SEGS was largely thanks to the commercial opportunities created by both federal and state legislation in the U.S [83]. These plants have productions that go from 14 MW in the first plants, to 30 MW in the later phases and finally of 80 MW in the last two complexes. Together, the SEGS platform can provide a total power of 354 MW.

Figure 1.14: Solar Energy Generating Systems solar power plants III-VII at Mojave Desert, California. Source: Alan Radecki Akradecki, Wikimedia [84]

The 2nd solar parabolic trough thermal plant built in the US was Nevada One, located in Eldorado Valley, Nevada. This 64 MW, property of ACCIONA [85] was connected to the network in 2007.

The three Andasol plants, located in Guadix (Spain), were built later, starting its production in 2008, 2009 and 2011. These plants have a capacity of 50 MW and Thermal Energy Storage (TES) for 7.5 hours each [86–88].

Figure 1.15: Andasol Solar Power Station, Guadix (Spain). Source: BSMPS, Wikimedia [89]

Solar thermal technology has now passed its development phase and is now in operation, Parabolic Trough Power Plants (PTPP) being by far the most developed of all the CSP technologies in commercial applications with more than 100 plants in production around the world in 2017 [90].

Some of the PTC CSP plants that have been built over the last few years and are currently in operation are:

1. Without TES:
    - Helioenergy 1 and 2 (50 MW, 110 hectares and 90 loops each), Seville (Spain) [44, 91].
    - Solaben 1, 2, 3 and 6 (50 MW, 110 hectares and 90 loops each), Cáceres (Spain) [46, 92–94].
    - Majadas I (50 MW, 135 hectares and 99 loops), Cáceres (Spain) [95].
    - Mojave Solar Project I and II (140 MW each, 357 hectares and 282 loops each), California (USA) [96, 97].
2. With TES:
    - Termesol 50 (50 MW, 230 hectares, 156 loops, 7.5 hours of thermal storage capacity), Cádiz (Spain) [98]
    - Kaxu (100 MW, 310 hectares, 300 loops, and 2.5 hours of thermal storage capacity), Pofadder (South Africa) [99].
    - NOOR I (160, 458 hectares, 400 loops and 3 hours of thermal storage capacity) and NOOR II (200 MW, 600 hectares, 425 loops and 7.3 hours of thermal storage capacity), Ouarzazate (Morocco). [47, 100, 101]
    - Solana Generating Station (280 MW, 780 hectares, 808 loops and 6 hours of thermal storage capacity), Arizona (USA) [45].

1.2.3 Current challenges in solar energy development and industry

The use of solar energy is one of the great challenges facing today's society due to its abundance with the clear objective of reducing the CO2 emissions produced by the conventional electric generation industry.

The solar thermal renewable energy industry is facing many problems in the massive production of electric power. One of the most significant issues is the cost per kWh or MWh. The costs of producing electricity in solar thermal power plants are not yet competitive in comparison with conventional fossil fuel plants. In fact, one of the great challenges of the century identified by the National Academy and the European Commission is to make solar energy economical and competitive. [102, 103]. Another aspect that commercial solar plants have to face is the temporary availability of the radiation resource [104]. This means that the production of the solar plants may not be as constant as in conventional fossil fuels plants with the corresponding economic losses and stability in the electricity grid. Therefore, it is important to emphasize the great effort that is being made both at the research and industrial level in the development of improved thermal energy storage units that will contribute to a more stable production even when there is no solar radiation.

The application of advanced control and optimization algorithms can play an important role in improving the overall efficiency of solar energy thermal plants and thus improving the penetration of these kind of plants into the global market [1]. If in addition, the research and development of new and improved thermal energy storage systems, as well as the optimization of their loading and unloading by means of advanced control techniques, could considerably increase the number of hours of electrical production, which would imply a reduction in the production costs per MWh making the thermosolar technology [105] more competitive and attractive.

Actually, both the research groups and the solar industry focus their efforts on solving the following problems, among others:

- Improve the efficiency of solar collectors. Whether thermal or photovoltaic technology.
- Improve the efficiency of the conversion cycles of the radiation captured in both thermal and photovoltaic.
- The development of improved and new energy storage systems. In this case, in solar thermal is Thermal Energy Storage (TES), and in photovoltaic it is Battery Energy Storage System (BESS).

- The optimization of the operation of the electric generation processes in solar plants.
- The reduction of design, manufacturing and installation costs.

In PTC CSPs, The efficiency of the solar collector is related both to the tracking system and to the construction materials of the parabolic mirrors, which have a form factor that indicates the level of perfection with which it was built. This factor is usually found in a value close to unity (it is taken as efficiency) but never equal to one due to imperfections, so that part of the efficiency in the solar rays collection is lost due to this imperfection in the mirror manufacturing. On the other hand, the reduction of installation costs is closely related to the use of wider aperture trough collectors [90].

The optimization of the performance of the generation processes can be obtained partially through the use of optimal control strategies of the solar field. It is said partially since the solar plant is composed of two main parts, as already mentioned, the solar phase and the steam phase. In the steam phase, the performance improvement refers to the optimal use of the different elements that make up this system, such as the turbine, the different heat exchangers, condensation phase, expansion stage, steam overheating, etc. Classical control systems such as PIDs are not optimal strategies for maximizing the performance of the solar field due to its simplicity and reactivity in the control. Solar plants contain highly nonlinear dynamics and variable time delays that depend on the HTF flow. One of the main problems in the control of the solar fields is the appearance of antiresonant modes that are problematic when it comes to obtaining fast and stable behavior of the solar field [106, 107].

It is also essential to bear in mind that current commercial solar trough cover vast extensions of land. In the case of the two solar trough plants of Mojave cover 700 hectares and they are composed of 282 loops each [96]. The solar trough plant SOLANA is even larger. It is composed of 808 loops covering 780 hectares [45]. These large-scale solar plants show up new challenges for the application of advanced control strategies. New advanced control techniques have to be devised and developed to address these issues.

In order to develop new advanced control strategies for large scale solar plants, The Advanced Grant Optimal Control of Thermal Solar Energy

Systems (OCONTSOLAR) funded by the European Research Council, is being conducted by the ”Model Predictive Group” at the Systems and Automatics Engineering Department, University of Seville, Spain. This thesis is framed and financed by the OCONTSOLAR project. One of the main objectives of this project is to develop radically new model predictive control (MPC) algorithms which use mobile solar sensor to obtain estimations and predictions of the solar radiation mapping [108]. In general, the control strategies proposed in the literature use the direct solar radiation provided by pyrheliometers. They consider that this measurement is the same for the whole solar field. If the solar field is small, such as the ACUREX field, this assumption can be considered reasonable, but in large scale plants different levels of solar radiation affect the solar field due to passing clouds. Furthermore, the efficiency of the loops can be substantially different because a group of them has been cleaned whereas another has not been [70]. The most efficient loops have to be defocused to avoid excessive temperatures. Paradoxically, the most efficient loops will have the higher energy losses. To avoid this energy loss, the valves of the most efficient loops would have to be opened to increase the HTF flow. However, any movement of the valve in one of the loops will influence the flow of the rest of the loops. Loop valves are only used in current plants for steady state flow balancing.

1.3 Thesis Objectives

The objectives of the thesis are mainly focused on the development of new model predictive control strategies and optimization of large-scale parabolic solar plants.

In the first part novel control algorithms are proposed for the control of the defocusing of the parabolic trough collectors as well as a control strategy for an operation mode which has not previously been taken into account in the literature, power limitation, which restricts the possibility of maximizing the production of the plant since the plant is forced to reduce the efficiency of the solar field in certain seasons of the year.

It is important to keep the oil temperature within the safe temperature limits provided by the manufacturer and to avoid its degradation. To prevent the temperature from exceeding the degradation limit, commercial plants have a safety strategy: collector defocus. This is applied in a staggered manner as total or partial defocusing, which is done by modifying the angle of the collector. Given that, in commercial plants, this is considered to be a safety mechanism, it is usually carried out only on the basis of thresholds. This mechanism of defocusing the collector is reactive and highly inefficient due to the thermal jumps caused by the application of full or partial defocusing and may cause oscillations in the outlet temperature of the loops [109, 110].

Commercial plants loops are, generally, formed by four solar collectors. Generally, the defocusing action of the fourth collector is, in normal situations, sufficient to control the outlet temperature around a set-point, avoiding exceeding the established thermal limit. MPC controllers are proposed for the defocusing of the fourth collector, avoiding the use of techniques based on partial or total defocuses. The proposed controllers have been simulated using a nonlinear model of a large-scale 50 MW plant composed of 90 loops.

However, when power limitations appear, defocusing the fourth collector is not enough to avoid exceeding the safe thermal limit of the HTF, and the third collector defocus has to be applied. This is due to the fact that to reduce power it is necessary to reduce the HTF flow-rate of the plant as it is directly related to the electrical power generation [109, 110]. Generally, power limitations appear when the electrical grid is saturated and they are commanded by the Transmission System Operator (TSO). 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 situation the objective is double: fulfilling the TSO power set-point and temperature tracking. Therefore, controllers are also proposed for the defocusing of the third collector and for the control of the electrical power generation in cases of power limitation.

The second part of the thesis focuses on the optimization of parabolic trough plants. The optimization of large-scale solar trough plants operation poses important challenges which requires new advanced control techniques to address them:

- The optical efficiency of different groups of loops may be substantially different in large scale solar plants. The most efficient loops will probably have to be defocused to avoid excessive temperatures.

Paradoxically, the most efficient loops will have the higher energy losses because of defocusing. To avoid this energy loss, the valves of the most efficient loops would have to be opened to increase the HTF flow. However, any movement of the valve in one of the loops will influence the flow of the rest of the loops. Loop valves are only used in current plants for steady state flow balancing.

- Scattered clouds may only affect the locations where the sensors are placed, while the rest of the plant may be under the effect of intense DNI, or vice versa. Sudden changes in DNI produced by scattered clouds induce oscillations so severe that the solar field may have to be defocused or shutdown. This fact tends to cause not only energy losses but plant deterioration. A spatially distributed DNI nowcasting can be used to improve the plant operation and optimizing the production.

Optimization algorithms are proposed for the control of the inlet valves of each of the loops in order to homogenize the solar field outlet temperature, or what is the same, a thermal balance of the solar field. This balance will decrease the high temperature gradients between the different loops as well as the possible loss of energy due to the defocusing of part of the solar field with higher optical efficiency or higher solar radiation. The proposed algorithms have been simulated using the ACUREX model in a preliminary phase, and adapted to a 50 MW plant in a second phase as a case study. It is shown how the proposed strategy is valid both for when the thermal unbalance is produced by the difference in the overall efficiency of the loops and when there is cloudiness affecting only part of the solar field (spatially distributed DNI).

In addition to the controllers, different techniques have been used to perform estimations of the temperature and reflectivity or efficiency of the loops. Model based and data driven or machine learning observers have been applied such as the Lumped Parameter Model, the Unscented Kalman Filter, Classification and Regression Trees and Fuzzy Logic.

1.4 Thesis Organization

This section details the organization of the Thesis.

In Chapter 2, the models of parabolic trough solar plants used as the main platform for the simulation and design of controllers and estimators are described: (1) the ACUREX solar field sited in Almería (Spain) (PSA-CIEMAT), and (2) a large-scale 50 MW solar plants composed of 90 loops. The mathematical description of concentrated and distributed parameters models that are used throughout the thesis are described. Chapter 3 presents Gain-Scheduling Generalized Predictive Controllers (GS-GPC) based on events for the control of the defocusing of the third and fourth collectors of the loops of a 50 MW field as well as for the control of the generated electrical power when the TSO commands power limitations. Chapter 4 proposes an improvement in the control of the defocus control proposed in chapter 3 through the use of an adaptive state space MPC control scheme. Among the improvements, an estimator of the reflectivity of the collectors by means of the concentrated parameters model to improve the adaptation of the model of the space of states at each moment as well as the estimation of the states of the plant (temperatures) using an Unscented Kalman Filter (UKF) are proposed. In Chapter 5 a preliminary study of the proposal of a nonlinear model based optimization algorithm for the homogenization of the outlet temperature of the solar field loops of ACUREX. This is done by controlling the inlet valves taking into account that the global optical efficiency of the loops do not have to be the same. The estimation of the temperatures is obtained by means of a Classification and Regression Trees which is previously trained with data obtained from the simulation of the distributed parameter model. In Chapter 6 modifications are made and the optimization algorithm is adapted for use in large-scale solar trough plants. It is applied to a 50 MW plant simulation model and the advantages of applying a model-based optimization technique for the control of the inlet valves of the loops are presented, as well as the problems that arise in plants with a large number of loops. Chapter 7 presents the problem of solar radiation in large and very large-scale fields. Due to the large size of solar plants, parts of the field may be covered by clouds (temporarily) while other areas will not. Similarly, it is possible to apply online optimization algorithms for the control of the inlet valves as the cloudiness penetrates certain areas of the field, avoiding energy losses, high temperature gradients and decreasing the defocus control actions. Finally, Chapter 8 presents the conclusions of the work carried out in this Thesis and future lines of work.

1.5 Main Contributions

This thesis focuses on the following contributions:

1. Development of Gain-Scheduling Generalized Predictive Controllers (GS-GPC) based on events for the defocus control of the third and fourth collectors of the loops of a 50 MW commercial solar plant as well as for the control of the generated electrical power when the TSO commands power limitations.

2. Improvement of the GS-GPC defocus control strategy through the use of an adaptive state space MPC control scheme.

3. An estimator of the reflectivity of the collectors by means of the concentrated parameters model to improve the adaptation of the model of the space of states at each moment as well as an estimator of the states of the loops temperatures using an Unscented Kalman Filter (UKF) are proposed.

4. A nonlinear model based optimization algorithm for the homogenization of the outlet temperature of the solar field loops. This is done by controlling the inlet valves taking into account that the global optical efficiency of the loops do not have to be the same.

5. An estimator of the temperatures by means of a Classification and Regression Trees, previously trained with data obtained from the simulation of the distributed parameter model, is proposed.

6. A model-based optimization technique for the control of the inlet valves of the loops to achieve a solar field thermal balance, in large scale solar trough plants, is presented. A clustering technique is applied to reduce the number of decision variables in the optimization problem.

7. An online optimization algorithm for the control of the loops inlet valves is designed, for large scale solar trough plants, to thermally

balance the solar field as the cloudiness penetrates certain areas of the solar field, avoiding energy losses, high temperature gradients and decreasing the defocus control actions.

1.6 Publications List

The following articles have been published or sent for publication during the development of this thesis:

Journal articles:

1. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Temperature homogenization of a solar trough field for performance improvement.* Solar Energy., 165C:1–9, May 2018.
2. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Event based mpc for defocusing and power production of a parabolic trough plant under power limitation.* Solar Energy, 174:570–581, November 2018.
3. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Adaptive incremental state space mpc for collector defocusing of a parabolic trough plant.* Solar Energy, 184:105–114, May 2019.
4. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Thermal balance of large scale parabolic trough plants: A case study.* Solar Energy, (Submitted to Solar Energy, Elsevier, June 2019).

Conference articles:

1. A. J. Sánchez, J. M. Escaño, N. Canty, A. J. Gallego and E. F. Camacho. *Solar radiation estimator and fault tolerant model predictive control of a parabolic-trough field.* 26th Irish Signals and Systems Conference (ISSC), pp:1-7, June 2015.
2. A. J. Gallego, L. Yebra, E. F. Camacho and A. J. Sánchez. *Mathematical modeling of the parabolic trough collector field of the tcp-100*

research plant. In Conference: Modelling and Simulation - 9th EUROSIM 2016, at Oulu, Finland, September 2016.

3. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Fault tolerant MPC of a solar trough field based on classification and regression trees*. 3rd Conference on Control and Fault-Tolerant Systems (SysTol), pp:152-157, September 2016.
4. A. J. Sánchez, J. M. Escaño, C. Bordons and E. F. Camacho. *Estimador borroso de una planta solar cilindro-parabólica*. XXXIX Jornadas de Automática, Universidad de Extremadura, Badajoz, España, Septiembre de 2018. *Award: Best paper in intelligent control.*

Book chapters:

1. E. F. Camacho, A. J. Sánchez and A. J. Gallego. Chapter title: *Model predictive control of large scale solar trough plants*. Book: *Solar Energy Systems: Progress and Future Directions*. Nova Science Publishers, Inc, New York, USA, (Submitted and accepted for publication).

Chapter 2

Solar trough field models

1. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Event based mpc for defocusing and power production of a parabolic trough plant under power limitation.* Solar Energy, 174:570–581, November 2018.

Chapter 3

Event based GS-GPC strategy for defocusing and power production

1. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Event based mpc for defocusing and power production of a parabolic trough plant under power limitation.* Solar Energy, 174:570–581, November 2018.

Chapter 4

Incremental State Space MPC for defocusing of a parabolic trough plant

1. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Adaptive incremental state space mpc for collector defocusing of a parabolic trough plant.* Solar Energy, 184:105–114, May 2019.

Chapter 5

Temperature homogenization of Acurex field for performance improvement

1. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Temperature homogenization of a solar trough field for performance improvement.* Solar Energy., 165C:1–9, May 2018.

Chapter 6

Thermal balance of large scale parabolic trough plants: A case study

1. A. J. Sánchez, A. J. Gallego, J. M. Escaño, and E. F. Camacho. *Thermal balance of large scale parabolic trough plants: A case study.* (Submitted to Solar Energy, Elsevier, June 2019).

Chapter 7

Thermal balance of a solar trough field under cloud coverage

1. E. F. Camacho, A. J. Sánchez and A. J. Gallego. Chapter title: *Model predictive control of large scale solar trough plants*. Book: *Solar Energy Systems: Progress and Future Directions*. Nova Science Publishers, Inc, New York, USA. (Submitted and accepted for publication).

Chapter 8

Conclusion

In this thesis MPC strategies and optimization algorithms based on non-linear models have been developed and presented for specific control systems and operation modes in solar trough plants that had not previously been taken into account. For the design of the control strategies proposed in this thesis, a simulation model of the ACUREX experimental solar plant has been used in the Plataforma Solar de Almería which is well known and has been used in numerous research works. In addition to this model, a simulation model of a 50 MW commercial plant has been presented. This model has been used extensively in the thesis to design, simulate and present the results of the proposed control schemes.

One of the most important factors in solar trough plants is the temperature of the thermal oil or HTF. Commercial solar plants produces energy around a nominal operating point in which the solar field temperature is high and close to the thermal limit of the HTF, tipically around 393 °C. Since the commercial plants are designed, generally, oversized to obtain an annual average performance determined by the company, in the summer season, late spring and early autumn, the plant will reach the maximum available flow-rate and there will be an excess of energy received in the solar field. If the solar plant has TES devices, it will be able to cope with this energy excess by diverting part of the flow-rate to the TES while the turbine continues to produce the maximum power. However, in solar plants without TES, this is not possible as there is no place to divert the flow-rate , therefore a mechanism to prevent the temperature of the HTF from exceeding the safety limits is needed. To prevent the temperature from exceeding the degradation limit, commercial plants have a safety strategy: collector defocus. This is applied in a staggered manner as total or partial defocusing based on temperature thresholds.

However, applying the defocus control in this way can lead to oscillations in the outlet temperature of the loops. In this thesis two types of controllers have been presented for the defocusing of the collectors for loop outlet temperature set-point tracking instead of applying control signals based on thresholds. An Event-based GS-GPC and an Adaptive Incremental State Space MPC. Both controllers have been simulated in the 50 MW model. The two controllers have shown a good behavior in the tracking of the loop outlet temperature with a smooth control, avoiding reaching the security limit. The state space MPC has shown a similar level of control performance to that of the EGS-GPC although with certain improvements. The EGS-GPC controller is somewhat inferior (ITAE and ISE indexes values are higher) to the MPC in the state space since, although it is based on global linear models at different operating points (Gain Scheduling), its performance may vary due, among others, to modeling errors and other factors that are considered in the EGS-GPC as the efficiency of the loops.

In general, in the literature, the efficiency of the loops has been assumed constant and equal in all loops. This can be a valid assumption for small-size solar fields. However, throughout the thesis it has been taken into account that the efficiency can be different in each loop due to cleaning factors (reflectivity) and condition of the mirrors. It is convenient to take into account this type of differences in large scale solar fields since they may affect the control performance of the solar plant. For this, different estimators of the efficiency of the loops (or collectors) have been applied depending on the needs of each control strategy. In some cases, an efficiency estimation has been applied by means of an optimization based on a non-linear model due to the fact that sufficient time was available for its computation. In other cases, the concentrated parameter model has been used due to the demands of the sampling times of the controllers. Both have proven to provide good results in the estimation and have been included into the control strategies in order to have an adaptive control model.

Throughout the thesis it has been commented that on some occasions, a commercial solar plant may receive a power limitation from the TSO. These commands make the plant move into an operation mode in which the objective is not maximum production. In these cases, the plant is forced to decrease its electric production and maintain the power set-point commanded by the TSO. Therefore a double objective problem arises: (1) temperature tracking and (2) generated power set-point tracking. The plant will have a time period to reduce its generated electric power to the set-point determined by the TSO. In this mode, the flow-rate should be decreased until the power set-point is achieved but at the cost of increasing the outlet temperature. These orders must be met, otherwise the plant will face economic sanctions. For the control of electrical power, an Event-based GS-GPC control scheme has been proposed in this thesis. In this case, given that the plant has a time to reach the established limit, it is possible to apply to the predictive controller a ramp of future references in each sampling time which allows a better control of the power thanks to the use of the sliding horizon of the model predictive control scheme.

Small solar fields such us the ACUREX field can be considered as one single equivalent collector loop in order to obtain an overall dynamic model and design control strategies in which the temperature to be controlled is the weighted average temperature of the loops. This approach is reasonable when the solar field is relatively small. Parameters such as efficiency of the receiver tubes, reflectivity or the shape factor of the collectors can be considered quite similar for all loops. Another important point is that the DNI is measured locally by pyrheliometers. Considering that all the solar field is affected by similar levels of solar radiation is reasonable in small plants but not in large solar fields. In large scale solar plants the flow-rate controller, usually design as it has been stated above, may cause energy losses or unnecessary overreaction due to the temperature discrepancy between the different loops. This effect occurs not only due to the difference between the loops but also due to clouds. Controlling the average temperature of all loops presents a drawback: if the solar field does not have a good thermal balance, due to differences in the loops optical efficiencies or partial clouds over the solar field, some loops may reach much higher temperatures than the others. The optical efficiency of the loops can be different due to aspects such as reflectivity, efficiency of the tube, shape factor and structural state of the collectors/loops. These imbalances in the optical efficiency may lead to the most efficiency loops to be defocused to avoid overheating problems.

In this thesis, control strategies based on non-linear optimizations have been presented for the control of the flow inlet valves to each of the loops. In commercial solar trough plants, the input valves are generally used to achieve a hydraulic or static thermal balance. Although this is normally done on rare occasions. It has been shown, by simulations, that a thermal balance of the solar field can be achieved (homogenizing loop temperatures) by applying the proposed optimization algorithm based on a simplified non-linear model to control the inlet valves aperture. In addition to avoid large temperature gradients between the loops, it is also possible to avoid energy losses (in certain occasions) as well as to reduce or completely eliminate the defocusing actions applied to each of the collectors, which will imply a life extension of the actuator. For the design of these optimization strategies, a clustering algorithm (K-Means) was used to group the loops according to their similarity in certain variables and parameters. Decreasing the number of decision variables in a non-linear optimization problem reduces computation times and can be adjusted to the desired control sampling times. This strategy has been applied for cases of differences in the efficiency of the loops as well as for cases in which partial clouds covers part of the solar field leaving another part of the field free of transients. In each of the cases, different sampling times have to be used since the needs of the problem to be solved are different.

Future Works

Some of the research lines to follow as a continuation of this thesis are:

1. Complete analysis of the effects of defocusing. Although two MPC strategies have been developed for defocus control, it is a system that has barely been touched in the literature. A deeper analysis of the problem is necessary. In this thesis has been applied to the third and fourth collector, which is the normal procedure in commercial plants. However, it may be interesting to analyze the first and second collectors. It will be studied if by applying fixed defocusing signals in the first two collectors, similar results can be obtained with lower control signals from the actuators. The temperature reference setpoints will be studied more carefully to find the optimal temperature references that may vary according to the operating modes.

2. Distributed optimization strategies for thermal balance of the solar field (OCONTSOLAR project). Valve control would be carried out through a distributed optimization based on nonlinear models. In this way, it is expected to be able to further reduce the computation time of the optimization problems in order to increase the number of decision variables that can be used. It is an important point because there are plants with up to 808 loops which will require high computation times.

3. Optimization strategies for thermal balance using game theory (OCONTSOLAR project). Similar to how it was done with the clustering of the valves, coalitions could be applied to the solar field loops. The

number of agents in the coalitions would change dynamically depending on factors such as reflectivity, defocus and cloudiness among others.

4. Integration of the proposed strategies with the radiation estimates generated by UAVs (OCONTSOLAR project). By making use of the spatial estimation of the solar radiation of the field and/or having a short term forecasting, much more anticipatory controllers could be obtained to avoid energy losses loss, more stable plant operation and to avoid undesired effects in the temperatures of the solar field.

5. Another point to develop is in the topic of temperature estimates. In this thesis data-based techniques (CARTs) and model-based (UKF) observers have been used. It is true that the performance of the UKF is indisputable due, among others, to the use of a simplified nonlinear model and its adaptation to the state of the plant at all times. However, it has the disadvantage of the computation time. Given that the OCONTSOLAR project is focused on the development of new control algorithms for plants with large extensions, the number of loops to control will be very high. When applying new controllers the estimates of the temperatures of the loops segments may exceed the sampling times of the controllers. Although the observer based on CART has shown good results, the size that it can occupy in memory is a disadvantage. Although fast-track observers have already begun to be develop, as a fuzzy observer in [161], it remains an observer based on static data and therefore research on data driven observers with reduced computation times that can include plant dynamics will be continued.

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