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Control of thermal solar energy plants

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ABSTRACT

This work deals with the main control problems found in solar power systems and the solutions proposed in literature. The paper first describes the main solar power technologies, some of the control approaches and then describes the main challenges encountered when controlling solar power systems.

1. Introduction

The use of renewable energy, such as solar energy, experienced a great impulse during the second half of the seventies just after the first big oil crisis. At that time, economic issues were the most important factors and the interest in these types of processes decreased when oil prices fell. There is renewed interest in the use of renewable energies nowadays driven by the need of reducing the high environmental impact produced by the use of fossil energy systems.

The most abundant, sustainable source of energy is the Sun, which provides over 150,000 terawatts of power to the Earth; about half of that energy reaches the Earth surface while the other half gets reflected to outer space by the atmosphere. Only a small fraction of the available solar energy reaching the Earth surface would be enough to satisfy the expected global energy demand. Although most renewable energies derive their energy from the Sun, by solar energy we refer to the direct use of solar radiation. One of the greatest scientific and technological opportunities we are facing is to develop efficient ways to collect, convert, store, and utilize solar energy at affordable costs [1].

There are two main drawbacks to solar energy systems: (a) the resulting energy costs are not yet competitive and (b) solar energy is not always available when needed. Considerable research efforts are being devoted to techniques which may help to overcome these drawbacks; control is one of those techniques.

While in other power generating processes, the main source of energy (the fuel) can be manipulated as it is used as the main control variable, in solar energy systems, the main source of power which is solar radiation cannot be manipulated [2] and furthermore it changes in a seasonal and on a daily base acting as a disturbance when considered from a control point of view. Solar plants have all the characteristics needed for using advanced control strategies able to cope with changing dynamics (nonlinearities and uncertainties). As fixed PID controllers cannot cope with some of the mentioned problems, they have to be detuned with low gain, producing sluggish responses or, if they are tightly tuned, they may produce high oscillations when the dynamics of the process vary, due to environmental and/or operating condition changes. In some cases, especially with high solar radiation and scattered clouds, oscillations are so severe that the field may have to be defocused or shutdown. The use of more efficient control strategies resulting in better responses would increase the number of operational hours of the solar plants and thus reduce the cost per kW-h produced, not only because of low radiation levels, but of the oscillations due to disturbances produced by scattered clouds.

This work describes the main solar energy plants and the control problems involved and how control systems can help in increasing their efficiency. Some illustrative examples are given.

The paper is organized as follows: Section 2 describes the main technologies used for solar energy production. The main control problems encountered are described in Section 3. Section 4 focuses on some of the control problems found in solar towers while Section

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5 is devoted to parabolic trough collectors, with a real application of a model predictive control algorithm. Section 6 presents an algorithm obtaining the optimal operating temperature in solar trough plants.

2. Solar energy harvesting

Solar powered electrical generation can be done either directly, by the use of photovoltaic (PV) cells or indirectly by collecting and concentrating the solar power (CSP) to produced steam which is then used to drive a turbine to provide the electrical power.

The direct generation of electricity from solar energy is based on the photovoltaic effect which refers to the fact photons of light knock electrons into a higher state of energy. Although the first application of photovoltaic was to power spacecrafts, there are many PV power generation systems for everyday life applications such as grid isolated houses, pumps for water extraction, electric cars, roadside emergency telephones and remote sensing [3,4].

Concentrating solar thermal (CST) systems use optical devices (usually mirrors) and Sun tracking systems to concentrate a large area of sunlight onto a smaller receiving area. The concentrated solar energy is then used as a heat source for a conventional power plant. A wide range of concentrating technologies exist. The main concentrating concepts are: (a) parabolic troughs, (b) solar dishes, (c) linear Fresnels, and (d) solar power towers. The main purpose of concentrating solar energy is to produce high temperatures and, therefore, high thermodynamic efficiencies.

Both technologies, PV and CSP, have their advantages and drawbacks. They are summarized below [5]:

- Photovoltaic panels are able to collect both direct and diffuse radiation so that they can work even on cloudy days.
- The electricity in CSP systems is produced by a power conversion system delivering alternating current (AC). Photovoltaic panels produce direct current which must be converted to alternating current using a grid tie inverter in existing distribution grids that use AC. This may lead to an energy loss of 4–12% [5].
- CSP possesses an inherent capacity for thermal storage. Batteries for storing the electricity produced by PV are more expensive.
- The construction process and installation is simpler for PV than CSP systems. PV systems require less maintenance than CSP technology.

In [6], a technical and economical comparison of photovoltaic and concentrating solar thermal power systems is performed. The conclusion obtained is that solar thermal power plants are the best-cost solution in South Europe and North Africa with possible generation cost below 10 Eurocents/kWh. Tracked PV systems have some cost advantages in North Africa.

3. Solar plants control challenges

This section describes the main issues encountered when controlling thermal solar plants. The section concentrates on the solar side of the plant and not on the more conventional part. The main controls of solar plants can be classified into Sun tracking and control of the thermal variables.

The control system is one of the most important part of a solar plant. It is usually organized in various levels. In commercial trough plants of Abengoa Solar NT [15], the control system is divided into 3 levels. The first level is devoted to controlling, monitoring and supervising all the facility's processes. The second level manages and controls the position of solar field reflectors. It comprises a series of PLCs each one responsible of a portion of the solar field. The third level performs the local control of each reflector, tracking the position data that has been transmitted by the second level.

The algorithms for Sun tracking can be classified into two types, open-loop or closed-loop, depending on their mode of control [7]. Different types of Sun-tracking systems are reviewed in [8] and their pros and cons are discussed. It is shown that the most efficient and popular sun-tracking device was found to be in the form of polar-axis and azimuth/elevation types.

A solar tracker is a device that points a solar collector mechanism towards the Sun or directs reflector mechanisms in such a way that it reflects the maximum energy onto a collector device. The solar power received by a solar collector is equal to the solar radiation received at that location multiplied by the device's surface and by the cosine of the angle formed by the Sun rays and the normal surface. There are many types of solar tracking mechanisms with different accuracy. Power tower heliostats need a good degree of accuracy to ensure that the power is reflected on the receiver which can be situated hundreds of meters from the heliostat. Little accuracy is required for non-concentrating applications; in fact, most of these applications work without any solar tracking at all. Tracking can significantly increase the amount of energy produced, especially in the early morning and late afternoon when the cosine of the angle of the direct solar radiation with the normal surface is smaller.

Many fast algorithms for calculating of the solar position used in engineering which requires little computation can be found in the literature. There has been a number of algorithms proposed in literature [9–11] which increase the precision without incurring in high computational efforts. These algorithms work correctly for limited periods of time. There are also high-precision astronomical algorithms to compute the Sun position with an error smaller than 0.0003° over a very long period of time (2000 B.C. to 6000 A.C.) but they require a large amount of computation.

Closed-loop algorithms for Sun tracking are based on feedback control principles. Sensors such as CCD cameras or photo-detectors are used to sense the Sun position [12]. Experimental results demonstrates that tracking errors smaller than 0.1° and important gains in energy production compared to non-tracking systems can be achieved [7,13]. In [14], a novel closed-loop design of a dual-axis solar tracking PV system which utilizes the feedback control theory along with a four-quadrant light dependent resistor (LDR) is presented. The effectiveness of the Sun tracker was confirmed experimentally.

4. Solar power tower controls

A solar power tower (SPT) plant consists of the heliostat field, receiver unit, heat transfer, exchange and storage unit, steam and electricity production units and the integrated control system. Usually, each of the units has its specific control device. The integrated control system communicates with the different subsystems to coordinate the different units in such a way that the plant operates in a safe and efficient way.

Typically, a plant control system includes heliostat control and heliostat field dispatch optimization, water level control in receivers, main steam temperature control, steam supply pressure and temperature in heat storage system control under heat releasing conditions, and the main steam pressure control. The first three commercial tower power plants in operation, the 10 MW (PS10) and the 20 MW (PS20) plants (Fig. 1), designed, built and operated by Abengoa Solar [15], and the Gemasolar plant operated by Torresol Energy [16], both close to Seville in Southern Spain.

The master control system of a solar power PS10 plant in Spain consists of different levels. The first level, local control, takes care of the positioning of the heliostats when the aiming point and the