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Optimization of the size of a solar thermal electricity plant by means of genetic algorithms

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ABSTRACT

Solar thermal electricity technologies are attractive alternatives to produce electricity by means of a renewable source. One of these technologies is parabolic trough collectors. In Spain, the sale of solar electricity to the national grid is primed. There are three main parameters that affect the behaviour of these plants: area of solar collector field, capacity of thermal storage tanks and power of the auxiliary system. In this paper, a simplified model of the plant is used to optimize the size of its components that produces the maximum yearly profit. The use of traditional methods of optimization is not possible and genetic algorithms have been used. An important feature of the model is that the minimum level of the electricity production of the block of power can be fixed. Once the optimization has been performed, the traditional parameters that characterize the dimension of the plant are analysed (the solar multiple and the capacity factor). For a gross power of 50 MW, the optimum collector area varies between 583,000 m^2 and 749,860 m^2 with a thermal storage between 6.55 h and 13.46 h respectively. The economic benefit is always higher than 19.30 M€ per year and the cost of the electricity produced is about 18.5 c€/kWh.

1. Introduction

Conventional solar thermal electricity plants convert solar radiation into heat that is transferred to a heat transfer fluid (water or synthetic oil). The transfer fluid produces steam that is expanded in a Rankine cycle. There are two commercially available types of plants for electricity generation in the order of MW: heliostats with a central receiver, and parabolic trough collectors (see Ref. [1] for an overview of the parabolic trough collectors and their applications). Both technologies are currently working in Spain, and the second one has been proved since 80's at the "Plataforma Solar de Almería" and it is commercially available since 1984 in USA. The central receiver type is working commercially in Spain since 2007. Mills [2], presented a review of the solar thermal electricity technology.

The efficiency of the cycle is higher when the temperature and pressure of the vapour entering the turbine increase. The limit to this temperature is fixed by the heat transfer fluid that it is used in the collectors. Apart from that, the efficiency of the solar field decreases with temperature. Synthetic oils are used in parabolic trough collectors as a heat transfer medium between collectors and Rankine cycle. The limit to the temperature of the steam is 400 °C approximately. Important efforts are carried out to generate directly the vapour in the collector field. This technology is called "direct steam generation" (DSG) and it is expected to reduce the cost of the solar electricity produced by these plants. The advantages of DSG are:

- To elevate the limit of the operation temperature of the cycle, and consequently increase the efficiency.
- To diminish the initial cost of the plant because of the reduction of the number of heat transfer equipment.
- To reduce the auxiliary pumping cost.
- To eliminate the replacement cost of the synthetic oil.
- To eliminate the risk of contamination due to losses in the oil circuit.

Obviously the main problem to the growth of thermal solar plants is the cost. They require very high capital investments and the electricity production cost is lower in conventional fossil fuel plants (if externalities are not taken into account). This situation has been modified in Spain since Royal Decree 661/2007 that guarantees an incentive to solar electricity. A maximum price of 34.3976 c€/kWh can be obtained for the solar electricity sold to the grid. Nowadays there are more than 500 MW under construction in Spain.

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Nomenclature

Ac	solar collector area [m^2]
AIC	annualized investment cost [€]
BOP	block of power
C_{aux}	auxiliary boiler cost per kW [€/kW]
C_{cp}	BOP cost per kW [€/kW]
c_{cs}	cost of the solar field per m^2 [€/m^2]
C_d	variable thermal storage cost [€/hour]
C_s	land cost per m^2 [€/m^2]
CF	capacity factor [%]
cft	thermal storage cost (fixed for each tank) [€]
CICS	initial investment cost in solar field [€]
*CIP*Aux	initial investment cost in auxiliary boiler [€]
CIPB	initial investment cost in the block of power [€]
CITD	initial investment cost in the thermal storage tanks [€]
CS	initial investment cost in the land [€]
DSG	direct steam generation
EO	evolutionary optimization
I	yearly total income [€]
IC	total investment cost [€]
L	minimum level of production for the BOP [%]
LEC	levelized electricity cost [c€/kWh]
LF_i	load fraction of each hour [%]
n	lifetime of the plant [years]
NDH	nominal degree of hybridization [−]
NTAN	number of thermal storage tanks [−]
o_s	land occupation per m^2 of collector area. It includes the land required for two thermal storage tanks [m^2/m^2]
Pauto	percentage of self consumption [%]
P_{aux}	auxiliary boiler power [kW]
r	debt interest rate [%]
RS_i	1 if the electricity produced at hour *i* is sold; 0 if it is devoted to restart the plant
SC	stop counter
SM	solar multiple [−]
Sups	number of additional tanks over two [−]
TES	thermal energy storage capacity [hours]

Besides the collectors, the components that determine the cost and performance of thermal solar power plants are the storage and the auxiliary systems. None of them is required in a pure solar plant, but they contribute to increase the capacity factor (the ratio between the electricity produced during a year and the production at nominal conditions during the 8760 h of the year). The solar collector area and the storage capacity are related by means of the solar multiple (the ratio between the capacity of the solar collectors to produce thermal energy at nominal conditions and the thermal power required by the cycle also at nominal conditions). When the solar multiple is greater than one, a thermal storage is required to store the excess of thermal production. Montes et al. [3] have analysed the influence of the solar multiple on the performance of a DSG solar thermal plant when the plant operates at nominal power.

Bernal et al. [4] present a good review of methods of simulation and optimization of a methodological similar problem. A stand-alone photovoltaic system with batteries is studied calculating the net present cost and the levelized cost of energy. When the plant sells the electricity to the grid, the maximal economic benefit and the minimal levelized electricity cost can be obtained with different dimensions of the plant.

In this paper, genetic algorithms are used to calculate the optimal size of the solar collector area, the thermal storage and the power of the auxiliary system in a DSG solar thermal power plant, in order to maximize the yearly profit. Genetic algorithms have been used before in a variety of thermal problems [5]. In Refs. [6,7] this technique is applied to solar systems.

The gross nominal capacity of the plant is 50 MW but the method considers that the minimum electricity production can be fixed between 25% and 75% of the nominal capacity. The climatic conditions of Málaga (a Mediterranean city in the south of Spain) have been used to calculate the performance of the plant.

This work has been developed in the framework of a collaborative project (GDV-500) between German and Spanish enterprises and public research centres.

2. Modelling of the solar plant

Fig. 1 shows the elements of the solar plant to be optimized. In the solar field solar radiation is converted into heat. The condensate that comes from the block of power (BOP) increases its temperature and pressure, and so it is suitable to produce work again.

When the radiation level is insufficient to produce the required mass flow of steam, a thermal storage and an auxiliary power system are employed in parallel to produce the supplement of energy to the BOP. Thermal storage is designed to collect energy during daylight and dispatch it when necessary. This strategy increases the number of operation hours of the plant (capacity factor). The auxiliary system is a gas boiler that is designed to maintain a minimum temperature in the plant to reduce start up periods and to contribute to electricity generation. The minimum electricity production allowed is a parameter of the optimization method.

There are three independent variables to be calculated in the optimization process: the solar collector area in m^2 (Ac), the thermal energy storage capacity in hours (*TES*) and the power (kW) of the auxiliary boiler (P_{aux}). The objective function to be optimized is the yearly profit. The levelized cost of electricity is also calculated.

An evaluation model of the benefit is required to perform the optimization. A black box model of each component is used to implement the evaluation model. The original physical models are not available because of confidentiality reasons, and just an external description of the behaviour of each component is at our disposal. This fact is a handicap in our search for optimization.

2.1. Solar collector field

In this project the collector model ET-150 from Euro Trough consortium is selected. The efficiency of the solar collector is almost constant with the incident direct solar radiation. Theoretically, the efficiency also depends on the difference between the temperature of the working fluid and the ambient temperature. This dependence has not been taken into account.

A solar collector field based on direct steam generation technology was designed and simulated by DLR. Simulations have been performed by means of a discretization of the collectors with a finite volume approximation. It is based on an upwind scheme taking into account direct normal irradiation and transient effects over the collector field. Fig. 2 shows the basic collector line for the solar field.

The collector field is created by repeating this basic line many times. The field is made of an evaporating section which increases water temperature coming from the power block, till water saturation temperature, having a last section of collectors where saturated steam is generated by separation from water recycled to the inlet section. The final section is the superheating loop, which heats up the steam to 500 °C using water from the previous section to