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Research Paper

Simulation and comparison between fixed and sliding-pressure strategies in parabolic-trough solar power plants with direct steam generation

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HIGHLIGHTS

- An efficient quasi-dynamic model is applied to simulate parabolic-trough DSG plants.
- Results show that sliding pressure provides better performance than fixed pressure.
- Sliding pressure might increase 6–7% net annual electricity in DSG plants.
- The use of variable pressure in the condenser can provide about 1% additional gain.

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ABSTRACT

Direct steam generation in parabolic-trough solar collectors is a promising technology that can improve the efficiency of solar thermal power plants. In this technology, water is heated and evaporated through the solar field to feed a steam Rankine cycle or an industrial thermal process. Regarding its application for electricity production, two main methods are commonly considered to regulate the steam pressure at the turbine inlet: fixed and sliding-pressure. In addition, the sliding-pressure method allows two different versions: constant and variable pressure in the condenser. This study aims to simulate the behaviour of a solar thermal power plant with direct steam generation applying the proposed strategies, by comparing their annual performance in terms of electricity production. To this end, a quasi-dynamic model able to address transient conditions with low computational resources has been applied. This model has been developed in the TRNSYS software environment and reproduces the behaviour of both the solar field and the power block of a 38.5 MW$_e$ solar thermal power plant. The results of this analysis demonstrate that the use of sliding-pressure strategies for steam pressure regulation in solar plants with direct steam generation is more advantageous in terms of net electricity production than the fixed-pressure method.

1. Introduction

Solar Thermal Power Plants (STPPs) based on Parabolic-Trough (PT) collectors are nowadays a successful technology with more than 4000 MW$_e$ installed and in operation around the world [1]. Most of them operate with synthetic oil as heat transfer medium in receiver tubes, but recently other working fluids, such as water, are being investigated in order to improve the performance of PT technology and avoid the environmental issues of synthetic oils [2].

In direct steam generation (DSG), water is heated and evaporated through the solar field to feed a steam Rankine cycle or an industrial process, avoiding the need for heat exchangers and hence increasing the efficiency of the whole system [3]. In this way, a 5 MW$_e$ STPP [4] built in Kanchanaburi (Thailand) was connected to the grid in 2012 and constitutes the first experience of commercial plant with DSG in PT collectors.

The steam turbines commonly used in STPPs present two main options to regulate their inlet steam pressure at part-load conditions: fixed and sliding pressure. According to the recommendations for steam turbines, the control mechanism should be aimed

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Nomenclature

A_c	net collection area, m^2
c_p	specific heat capacity, J/(kg·K)
E_b	direct normal solar irradiance, W/m^2
F	proportionality factor, –
h	specific enthalpy, J/kg
K	gain coefficient, –
$K(\theta)$	incidence angle modifier, –
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
p	pressure, Pa
$\dot{Q}$	thermal power, W
t	time, s
T	temperature, °C
$\dot{W}$	electric power, W

Acronyms

DCA	drain cooling approach
DISS	DIrect Solar Steam
DNI	direct normal solar irradiance (equivalent to E_b)
DSG	direct steam generation
PI	proportional-integral
PSA	Plataforma Solar de Almería
PT	parabolic trough
STPP	solar thermal power plant
TTD	terminal temperature difference

Greek symbols

Δ	increment or variation
η	efficiency or performance factor, –
θ	incidence angle, °

Subscripts

amb	ambient
clean	cleanliness
error	deviation with respect to the set-point value
fluid	heat transfer fluid
gross	gross electric power
I	integral
in	inlet
loss	electric power losses
nom	nominal
old	value in the previous time step
opt,0°	peak optical
out	outlet
oper	operation
P	proportional
pipe	metal pipe
pump	pumping consumptions
ref	reference or set-point value
sh	shadowing
stop	related to the time interval when fluid circulation is stopped
u	useful

to keep the volumetric flow at the turbine inlet approximately constant. On the one hand, the fixed-pressure method is based on reducing the admission area of the first stage of the turbine by means of nozzle-governing valves, whilst maintaining the nominal inlet pressure. The steam admittance into the turbine governing stage is thus regulated with several valves, usually four, that are shut sequentially to control the steam flow [5]. On the other hand, the sliding-pressure strategy consists of decreasing the inlet steam pressure according to the mass flow rate in order to reduce the fluid density, hence maintaining a stable volumetric flow rate.

Up to date, several studies have been conducted to analyse the electricity production of STPPs with DSG, using either fixed [6] or sliding-pressure [7] strategies for the turbine inlet. As a conclusion, sliding-pressure is expected to show higher efficiencies at part-load behaviour of the power block, mainly due to valves throttling and aerodynamic losses in nozzle governing [5]. However, the regulation of the steam pressure in a DSG solar field for sliding-pressure strategies is thought to be slower and poses some uncertainties under transient situations that have not been yet specifically analysed.

In this way, this work aims to determine the impact of sliding-pressure strategies compared to the fixed-pressure method under the same design conditions. To this end, a hypothetical 38.5 MW$_e$ STPP using DSG in PT collectors is simulated. This plant includes a power block with a steam turbine whose behaviour under the proposed strategies is evaluated. The simulation applies a quasi-dynamic model developed in the TRNSYS software environment to calculate annual results of thermal and electrical energy.

The gross electric power selected for the plant, 38.5 MW$_e$, considers 35 MW$_e$ of net electric power plus 10% in electrical consumptions. Electric capacities recently adopted for STPPs with conventional heat transfer fluids usually range from 50 to 150 MW$_e$ [1]. However, in the case of DSG, given the high design pressure in the solar field and taking into account that a 5 MW$_e$ plant [4] is the only STPP with DSG in PT collectors in commercial operation, the requirements for larger plants in terms of header piping and working limits of critical components may involve a great technological leap. Moreover, economic analyses [8] comparing DSG to synthetic oil suggest that power capacities lower than 50 MW$_e$ for DSG technology could be more cost-effective for plants without storage. In order to be conservative, this work assumes that a DSG plant of medium size could be feasible with the current state-of-the-art technology and hence the aforementioned value chosen for gross electric power.

This paper is structured as follows: Section 2 describes the model of the solar plant to be simulated and the specific approach adopted for either fixed or sliding pressure. Section 3 summarizes the comparison of results between both strategies, together with a discussion about their impact on electricity production. Finally, brief conclusions are presented in Section 4.

2. Simulation model of the solar plant

The simulation model reproduces the thermal and hydraulic behaviour of each component of the plant including the main elements of the solar field and the power block. The model has been developed with the TRNSYS software tool [9], a graphically-based environment used to simulate transient systems. Models are created by connecting different components, providing a flexible tool that allows different configurations and sizes of the plant and an easy modification of details such as collector type, location, etc.

The STPP is composed of two main systems: a solar field with 40 collectors' loops of 1000 m of effective length (10 collectors of 100 m length per loop) with North-South orientation and a power block based on a Rankine cycle with a steam turbine of 38.5 MW$_e$. Each loop of the solar field works as a preheater, evaporator and super-heater of the feed water, using the solar energy as primary source of energy. The super-heated steam generated in the solar