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Modelling and dynamic simulation of a parabolic trough power plant

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A B S T R A C T

Investigational dynamic simulations of an existing 50 MW_{el} parabolic trough solar thermal power plant in Spain are carried out during clear days and slightly cloudy periods. This work is the first research, which presents a detail dynamic model of a parabolic trough power plant. Besides the thermal energy storage system and solar field, the developed model describes the heat transfer fluid and steam/water paths in detail. Advanced control circuits, including drum level, economiser water bypass, attemperator and steam bypass controllers are also included. The parabolic trough power plant is modelled using Advanced Process Simulation Software (APROS). The comparison between the simulation results and measured data is documented, showing a reliable prediction of the real behaviour of the investigated solar power plant. The validated model offers a possibility for accurate simulation of further operation processes of the real plant.

1. Introduction

The current international trends to replace the fossil fuels with renewable energy sources have continued to increase. This is due to the limited fossil fuel resources, the reduction of import dependency, the continuing growth of the world's population, the rising demand for energy and accordingly the carbon dioxide emissions which result. Furthermore, the special political support of renewable energies has become the touchstone in many countries. Among renewables, solar energy is considered as a main alternative to satisfy the energy demand for countries with high solar radiation.

Basically, solar energy technologies are divided into two types: concentrating solar power (CSP) and photovoltaic cells (PV). Both technologies use the direct normal irradiation (DNI) of the sun as a main source to generate electrical power. The main difference is that the photovoltaic cells convert the sunlight directly to electrical energy by means of semiconducting materials. CSP plants, by contrast, concentrate solar radiation by mirrors, which reflect the sunlight to absorber tubes. The solar radiation is converted to thermal energy, collected by a heat transfer fluid.

CSP technologies are divided into two main techniques, namely point-concentrating technology and line-concentrating technology [1], it can be briefly explained as follows:

1. point-concentrating technology
   a. Solar tower technology
      The solar tower power plant consists of heliostats and a receiver that is located at the top of the tower. Each heliostat includes several flat mirrors, which reflect the solar radiation onto the central receiver at the top of the tower. Heliostats track the sun movement by a sun tracking system along two axes to maintain high collection efficiency.
   b. Parabolic dish technology
      A parabolic dish reflector is a point-focus collector in a dish form. It follows the sun in two axes during daylight. The concentrating solar radiation is absorbed by a receiver. The thermal energy stored in a working fluid is converted to electricity through a Stirling engine or a gas turbine.
2. Line-concentrating technology
   a. Fresnel reflector technology
      Solar Fresnel reflector consists of a flat or a slightly curved Fresnel reflector (cylindrical-parabolic reflector). The solar radiation is reflected to a fixed receiver in the shape of long tubes. General features of a fixed receiver contain a simple piping system and flexibility to select the heat transfer fluid (HTF). A fixed receiver can operate with various types of HTFs, whether it is water (direct steam generation), thermal oil or molten salt. Particularly with the molten salt, it can be used in

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Nomenclature

A_c	the mirror aperture area for a single loop [m^2]
d_1	the spacing between consecutive SCAs in a row [m]
d_2	the spacing between consecutive SCEs in a SCA [m]
L_f	the focal length of the parabola [m]
L_{sca}	the length of mirror of a single SCA [m]
L_{space}	the space between rows in the solar field [m]
L	longitude [°]
$\dot{m}$	mass flow rate [kg/s]
T	temperature [°C]
t	time [s] in the equations, [hh:mm] in the results
$w_{sca,total}$	the total aperture width of a single SCA [m]
δ	sun declination [°]
θ_z	zenith angle [°]
θ_i	incidence angle [°]
ω	hour angle [°]
φ	latitude [°]
η_{PB}	power block efficiency [–]
$\eta_{opt,0}$	optical efficiency [–]
η_{track}	the tracking error (between 0 and 1) [–]

Subscripts

el	electrical
th	thermal

Abbreviations

APROS	advanced process simulation software
Attemp	attemperator
BFP	boiler feedwater pump
CSP	concentrating solar power
DNI	direct normal irradiation
ECON	economiser
EVAP	evaporator
FW	feed-water
FW MCV	feed water main control valve
HCE	heat collection element
HP	high pressure
HP Attemp CV	high pressure attemperator control valve
HPBPCV	high pressure bypass control valve
HPMSCV	high pressure main steam control valve
HP PH	high pressure preheater
HP PHCV	high pressure preheater control valve
HPRP	high pressure recirculation pump
HPT	high pressure turbine
HTF	heat transfer fluid
HTF MCV	heat transfer fluid main control valve
LP	low pressure
LP Attemp CV	low pressure attemperator control valve
LPBPCV	low pressure bypass control valve
LP PH	low pressure preheater
LPMSCV	low pressure main steam control valve
PB MCV	power block main control valve
PV	photovoltaic cells
RH	reheater
SH Attemp CV	reheater attemperator control valve
SCA	solar collector assembly
SCE	solar collector element
SF	solar field
SH	superheater
SH Attemp CV	super heater attemperator control valve
ST	steam turbine
TS	thermal storage
TS MCVi	thermal storage main control valve inlet
TS MCVo	thermal storage main control valve outlet
WS	water/steam

the thermal storage system. The aim of using these HTFs is for generating the steam, whether it is direct or indirect steam generation. The superheated steam operates a steam turbine, converting mechanical energy to electrical power.

b. Parabolic trough technology

Parabolic troughs consist of a series of curved mirrors and absorber tubes. While the heat transfer fluid (HTF) passes through a fixed absorber tubes, its temperature rises due to the concentrated solar radiation. As in Fresnel technology, a steam turbine is run by superheated steam, whether it is direct or indirect steam generation. Concentrated solar power is a promising option for energy production in regions with abundant solar radiation.

Currently, solar thermal power plants are providing Europe around 2.31 GW by 2014. In Spain, there is a clear trend towards the development of the solar thermal power plants, where 50 concentrating thermal power plants with a total capacity of 2.3 GW are now in operation. These plants distributed in 45 parabolic trough power plants with 2.222 GW, 3 solar tower plants with total capacity 50 MW and 2 linear Fresnel power plant with total power 31.4 MW. Also, there are 201 MW in construction and 930 MW under development [2,3].

Besides experimental work, mathematical models of thermal power plants contribute to a better understanding of the process, its capabilities and limitations. Optimisations and new designs of energy systems generally start with steady-state process simulation models. The steady-state models do not require control structures and are mathematically based on mass, momentum and energy balances. However, the transient and continuous changes in operating conditions will influence the efficiency of the investigated power plant. In order to analyse the process during various disturbance situations, the use of dynamic models is of high relevance. Dynamic models, in contrast to steady-state models, require the unsteady solution of three major conservation equations (mass, momentum and energy), the implementation of dynamic boundary conditions, control units and their associated components.

A recent literature review shows that there are several studies regarding the optimisation of the parabolic trough power plant employing steady-state models, while dynamic models are rarely presented. Price [4] developed a simulation model to evaluate the trade-off between cost, performance and economic parameters for a parabolic trough solar power plant. Furthermore, the model was applied to optimise the design of the thermal storage system. Montes et al. [5] presented a steady-state model with the aim of economic optimisation of the solar parabolic trough power plant. The model they developed was applied to investigate the influence of different solar field sizes on the thermal performance at maximum and part-load condition. Rolim et al. [6] proposed an analytic model for a solar thermal model with parabolic trough collectors. The model described the energy conversion of the solar radiation into thermal power plant along the absorber tube. Here, the nonlinearity of heat losses and its dependence on the local temperature is considered. The numerical results are compared with measurements obtained from Solar Energy Generating Systems VI, built at the Mojave desert, California, showing good agreement. Abutayeh et al. [7] presented a detailed model of a real solar thermal power plant using the steady-state power plant simulation software (IPSEpro). In the numerical model, the parabolic trough collectors track