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Dynamic modelling of a low-concentration solar power plant: A control strategy to improve flexibility

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ABSTRACT

This paper deals with a dynamic analysis on a low concentration solar power plants coupled with Organic Rankine Cycles (ORC), which can be an alternative to PV systems because of their capability of providing a smoother electricity production due to their thermal inertia. At least within certain restraints, moreover they are able to exploit diffused solar radiation.

The dynamic model of a plant with static Compound Parabolic Collectors and an ORC system, using a rotary volumetric expander, was developed using the simulation tool AMESim. All the main components of the plant are modelled: solar collectors field, heat transfer fluid circuit, heat exchangers and the ORC system. The plant response to the radiation of different days was analyzed to quantify the daily production and the trend of various plant parameters. Real ambient conditions were employed for the simulations by using data obtained by historical series.

The results showed that the employment of a volumetric expansion device with variable rotating speed allows the plant to operate at different radiations and ambient temperatures without the need of any storage system or external heat sources. Results can be extended to other applications, such as low temperature waste heat recovery or geothermal systems.

1. Introduction

The interest towards solar energy has been increasing in the last years. In the micro-generation field, Photo-voltaic (PV) systems are widely used due to their installation simplicity, simple management, and low costs of maintenance. However the lack of inertia of these systems and the unprogrammable nature of the source, are causing problems on the electric grid. Low concentration solar plants can limit fluctuations of delivered power because of their thermal inertia. Obviously, since we are talking about systems that are addressed to domestic or small industrial or commercial activities, simple, low cost and small size units have to be developed. Compound Parabolic Collectors (CPC) and volumetric expansion devices can help in the accomplishment of this objective. CPCs have been studied for several years [1,2] and are characterized by a wide operational flexibility [3]. Because of their wide acceptance angle, CPCs do not need any tracking system, and allow to reach higher temperatures with better efficiencies than flat plate collectors [4]. Volumetric rotary expanders are more suitable than micro-turbines for small power output applications, because of the higher isentropic expansion efficiency, lower rotational speed, lower costs [5–7] and wider possibility of control [8]. The variation of the rotational speed in particular can be easily achieved and keeps the isentropic efficiency of the device almost constant [9]. Using this control, the power output can be varied without the need of a storage system, simplifying the layout, saving space and reducing installation costs. Because of the strong variation of thermal input and the lack of a storage system or integration with an external source, it is important to consider the effective dynamic behavior of the system, in order to properly set parameters, improve performances and management.

Dynamic modelling in facts has become an important tool for solar plants and in general for applications characterized by large variations of the input power. Manenti et al. [10,11] carried out numerical simulations to perform the start-up operations of Archimede Concentrating Solar Plant in Sicily, using DYNSIM. In their papers they identified the critical aspects of start-up and shut-down operations and optimized the control strategy of the plant. El Hefni [12] employed ThermoSysPro - Modelica in modelling a solar plant with different type of collectors and a solar hybrid combined-

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Nomenclature

A	Exchange area (m^2)
C	Concentration
G	Global incident radiation (W/m^2)
i	Incident angle (°)
I_{bn}	Ground direct radiation (W/m^2)
I_{d0}	Ground diffuse radiation (W/m^2)
$\dot{m}$	Mass flow rate (kg/s^{-2})
p	Pressure (bar)
r	Ambient reflectivity (–)
t	Time (s)
T	Temperature (K)
u	Specific internal energy (J/kg)
U	Internal energy (J)
V	Volume (m^3)
$\dot{V}$	Volume flow rate ($m/3s$)
$\dot{W}$	Power (kW)
$\dot{Q}$	Thermal power (kW)

Subscripts

c	collector
el	electrical
exp	expander
is	isentropic
mec	mechanical
p	pump
ad	admission
sat	saturation
sh	superheating
r	receiver
rec	recuperator
a	actual
max	maximum

Greek

α	Solar height (°)
β	Collectors tilt angle (°)
η	Efficiency
λ	heat exchange coefficient (W/m^2 K)
ρ	Density (kg/m^3)

Acronyms

HTF	heat transfer fluid
PV	Photovoltaic
CPC	Compound Parabolic Collectors

cycle power plant with PTC collectors. Rodat et al. [13] simulated the dynamic response of two solar concentrating plants with Fresnel collectors in the Modelica environment. They monitored the temperature of the superheated steam after the cloud passage and highlighted the difficulty to tune a proper control systems to handle both slow and fast phenomena. Other authors focused on the optimization of a part of the plant: Eck et al. [14] studied the superheated steam control system of a PTC loop, Henrion et al. [15] used dynamic simulation in the design of an innovative evaporator, with a particular attention to start-up operations. Quoilin et al. [16] showed the possibility of controlling and optimizing a small power output Waste Heat Recovery system through the variation of the speed of a scroll expander.

This paper shows the numerical modelling of a 25 kW ORC solar plant by means of the AMESim simulation tool, showing the capability of the model of highlighting the optimal working condition of the plant from the point of view of the solar field parameters (concentration and tilt). This paper clearly indicates the need for a dynamic simulation which was able to evaluate the influence of warm-up period on the electrical production of the plant.

This work also demonstrates the effectiveness of the control strategy based on the rotating speed of the expander, which proved to be able of operating under variable radiation conditions, without the need for any storage system or integration with external heat sources.

The novelty which is introduced in this work consists in the application of this kind of simulation and control strategy in a small-size power plant, which employes non-tracking, low concentration collectors, whose parameters have been chosen in order to optimize the overall production along several working days. The conditions which have been taken as a reference were both ideal conditions (fully sunny day) and real ones, derived from historical series.

2. System description and fluids

The studied system consists of a non-tracking CPC field, an HTF circuit and an ORC (Fig. 1). The cycle is composed by a pump, an evaporator, an expansion device, a recuperator and an air-cooled condenser. Superheating and regeneration are employed because in a previously published work [17] they proved to improve the overall efficiency of the plant. The choice of the heat transfer fluid and of the working fluid is critical. In fact the heat transfer fluid should have good thermal properties to efficiently transfer the heat, high density and low viscosity to limit the pumping power loss. Since the maximum temperature of this system is expected to be about 160° C, pressurized water was chosen as heat transfer fluid. The working fluid is R-600a since it gave the best results in the stationary analysis of the plant [4].

The CPCs employed evacuated pipes to suppress convection losses as shown in a previous paper [4]. The number of collectors was chosen to provide the thermal input needed by the plant when the expansion device rotated at its maximum speed (3000 rpm). CPCs were arranged in arrays composed of 9 collectors linked in series, and each array was in parallel with the other, as reported in Fig. 2. A schematic view of an array tilted by a generic angle is reported in Fig. 3. In Fig. 4 the efficiency of the collectors provided by manufacturers is reported. The collector field outlet temperature was controlled by the circulating pump speed. The collectors were disposed in the East-West direction, for the sun rays to be incident on the CPC aperture within the acceptance angle [18].

The expander displacement and introduction grade, defined as in Ref. [5], were respectively 316 cm^3 and 0.2 and the rotational speed was varied in the range 500–3000 rpm. The velocity of the expander was used to control the evaporating pressure set point. An inverter is therefore needed to connect the plant to the grid. Condensing temperature was 15° C higher than the ambient temperature and therefore was variable during the day. The choice of a variable condensing temperature was possible since the expander is volumetric and the only restriction on the pressure ratio is given by over-expansion phenomena [19], which should be avoided by means of an appropriate value of saturation pressure [9].——-Frase riformulata—The choice of a variable condensing temperature does not have the effect of lowering too much the expander efficiency